

THE NEW MEXICO ENVIRONMENT DEPARTMENT



HEALTH ADVISORY FOR PRIVATE WELLS WITHIN THE SAN MATEO CREEK BASIN

Advisory

The New Mexico Environment Department ("NMED") cautions all present and future owners and users of private wells within the San Mateo Creek basin (see Figure 1) that your well water could contain some contaminant concentrations in excess of federal drinking water standards.

Possible contaminants that may occur in concentrations exceeding federal drinking water standards include chloride, gross alpha, lead, manganese, nitrate, pH, radium₂₂₆+radium₂₂₈, selenium, sulfate, total dissolved solids ("TDS"), and uranium; additional contaminants that have been detected for which federal drinking water standards have not been established include, iron, molybdenum, thorium₂₃₀, and vanadium. The sources of these contaminants in part may include naturally-occurring ore deposits within this portion of the "Grants uranium belt," as well as former uranium mines and mills within the basin that historically accessed these deposits.

Health risks for long-term exposure to gross alpha, lead, nitrate, radium, selenium, sulfate, thorium, and uranium contaminants that have been documented could include cancer; kidney, spleen, and liver damage; birth defects; systemic mineral imbalance; and digestive problems. Information regarding these contaminants in drinking water can be found at the U.S. Environmental Protection Agency (EPA) website, <http://www.epa.gov/safewater/dwh/>, and at the Agency for Toxic Substances and Disease Registry (ATSDR) website, <http://www.atsdr.cdc.gov/toxfaq.html>. Other contaminants listed above may cause only aesthetic effects to the appearance or taste of ground water.

Current and future private well owners and users are urged to have their well water sampled for concentrations of these contaminants. Persons who are considering installing a private well within the Advisory Area are urged to test well water for these contaminants. A list of certified laboratories for drinking water analyses can be found on the Internet at http://www.nmenv.state.nm.us/dwb/Certified_labs.html.

These recommendations only apply to private domestic wells. Public water supply systems for municipalities, and for some smaller communities such as some trailer parks, are regulated by the NMED Drinking Water Bureau and are routinely tested for regulated contaminant concentrations (i.e., those for which EPA has established primary Maximum Contaminant Levels ["MCLs"]) to identify any exceedances of federal drinking water standards. Information on regulated drinking water supply systems can be found on the Internet at <http://eidea.state.nm.us/SDWIS/>.

NMED is also in the early stages of investigations within the San Mateo basin in order to better understand, and potentially address, possible ground water contamination from past uranium mining and milling activities.

Additional information

The majority of information about ground water quality, as well as most current human consumptive usage, comes from private wells in subdivisions that are located in the southern part of this basin, within Cibola County north of the City of Milan. Other areas of this basin are sparsely populated, and little current data on ground water quality exist outside of former uranium mine and mill sites.

Since the 1970's, the U.S. Nuclear Regulatory Commission ("NRC") has required remediation of ground water contamination at the Homestake Mining Company uranium millsite. Under NRC regulatory authority, background concentrations of site-related contaminants have been established for the affected aquifers, and accepted by NMED and EPA. These background levels generally exceed MCLs, indicating that ground water contamination in excess of federal drinking water standards also exists upgradient of the Homestake facility from contaminant sources other than the Homestake facility, including both natural (e.g., ground or surface water passing through rocks from which naturally-occurring minerals become dissolved into the water), and potential manmade sources (e.g., both ground or surface water passing through and dissolving components of mine or mill wastes, and ground water that has been impacted by mine or mill effluents). Homestake is required to remediate site-related contaminants to the approved background contaminant concentrations in the aquifers affected by contamination from its millsite. However, ground water background contaminant concentrations in excess of federal primary MCLs within the San Mateo Creek basin are expected to persist after Homestake completes its remedial activities.

Limited recent ground water quality data from samples that have been collected in and near abandoned uranium mine shafts in the Ambrosia Lake area also indicate the occurrence of contaminants in concentrations exceeding MCLs within this area of the basin.

ALL PRESENT AND FUTURE OWNERS AND USERS OF PRIVATE WELLS THAT ARE LOCATED WITHIN THE ADVISORY AREA ARE ADVISED TO SAMPLE THEIR WELLS TO ENSURE THAT THE QUALITY OF WELL WATER DOES NOT POSE HEALTH CONCERNS.

For more information about public water supply systems, please contact:

New Mexico Environment Department
Drinking Water Bureau
Toll Free: (877) 654-8720 (toll-free)
<http://www.nmenv.state.nm.us/dwb/index.htm>

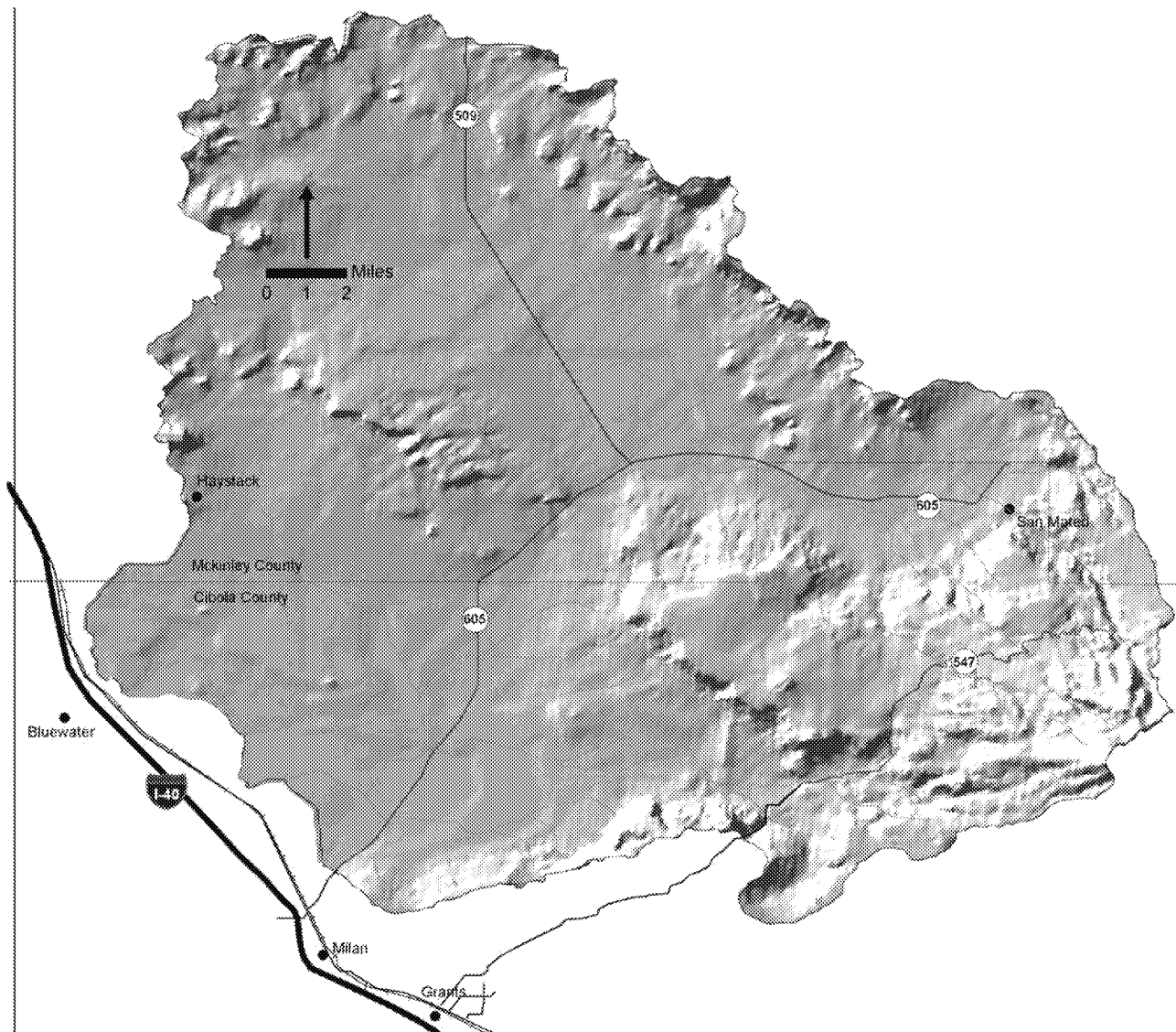
For more information about ground water abatement activities, please contact:

New Mexico Environment Department
Ground Water Quality Bureau
(800) 219-6157
(505) 827-2918
<http://www.nmenv.state.nm.us/gwb/gwqbhome.html>

For more information about the potential health effects of ground water contaminants, please contact:

New Mexico Department of Health
Epidemiology and Response Division
(800) 879-3421 (toll-free)
(505) 827-0006
<http://www.health.state.nm.us/index.html>

Figure 1: Private well health advisory area—San Mateo Creek Basin



Message

From: Winton, Ashlynn, NMENV [Ashlynn.Winton@state.nm.us]
Sent: 7/8/2019 5:28:05 PM
To: Vollbrecht, Kurt, NMENV [kurt.vollbrecht@state.nm.us]; Longmire, Patrick, NMENV [Patrick.Longmire@state.nm.us]
CC: Ehlert, Keith W., NMENV [KeithW.Ehlert@state.nm.us]; Purcell, Mark [purcell.mark@epa.gov]
Subject: FW: [EXT] Re: [EXTERNAL] USGS Report on Homestake Superfund site
Attachments: Blake 2019 EES Differentiating Anthropogenic and natural sources of U by geochemical fingerprinting of GW at the Homestake U mill.pdf

Hi all,

At long last – here is the USGS Geochemistry Report done for the Homestake Site. Please let me know who to forward this to.

Mark – I believe Johanna sent it to you as well , but just in case.

Ashlynn Winton, Environmental Scientist
Mining Environmental Compliance Section
New Mexico Environment Department
Ground Water Quality Bureau
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Santa Fe, NM 87502-5469
Office: 505.827.0602
ashlynn.winton@state.nm.us
<https://www.env.nm.gov/gwqb/>

From: Blake, Johanna <jmtblake@usgs.gov>
Sent: Monday, July 8, 2019 11:06 AM
To: Winton, Ashlynn, NMENV <Ashlynn.Winton@state.nm.us>
Subject: Re: [EXT] Re: [EXTERNAL] USGS Report on Homestake Superfund site

Hi Ashlynn,
Attached is the geochemistry paper from our work at the Homestake mill site.
Let me know if you have any questions.
Thanks,
Johanna



Differentiating anthropogenic and natural sources of uranium by geochemical fingerprinting of groundwater at the Homestake uranium mill, Milan, New Mexico, USA

Johanna M. Blake¹ · Philip Harte² · Kent Becher³

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Abstract

A multiparameter geochemical-isotopic fingerprinting approach was used to differentiate anthropogenic and natural signatures of uranium contamination near the Homestake uranium mill site (Site), near Milan, New Mexico, USA. The Site consists of two tailings piles from milling operations and groundwater contamination from these tailings has been noted. The Site lies within the lower San Mateo Creek Basin and has multiple regional sources of uranium contamination from mining and mill operations. The Site is underlain by a heterogeneous alluvial aquifer, which is in turn underlain by basement rock of the Chinle Group aquifer and the underlying San Andres-Glorieta Formation aquifer. To help decipher signatures, several statistical approaches were used including principal component analysis, non-metric multidimensional scaling, and cluster analysis. Piper diagrams indicate two end-member water types at the Site, sulfate–Na–K generally in the Chinle Group aquifer and sulfate–Ca generally in the alluvial aquifer. There are wells from both aquifers that plot between the two end members. Uranium concentrations from the Site fall into three broad categories: less than the drinking water standard of 30 µg/L ($n=3$), from 30 to 100 µg/L ($n=9$), and greater than 100 µg/L ($n=8$). Component loadings in a principal component analysis are highest for uranium isotopes, uranium, molybdenum, chloride, sodium, ²²⁸radium, and gross alpha–beta, which affect the similarities or differences among wells sampled. Results suggest that several alluvial wells north of the Site have groundwater with anthropogenic fingerprints from regional sources related to upgradient mining. Well water with higher uranium concentrations has uranium activity ratios close to 1, which is indicative of mining or milling signatures. These same wells have elevated radon activities. This information can be used to inform Site managers regarding the source of water related to uranium at the Site and provide an approach for geochemical fingerprinting.

Keywords Geochemical fingerprint · Uranium milling · Grants Mineral Belt · ²³⁴U/²³⁸U · Multivariate statistics

Electronic supplementary material The online version of this article (<https://doi.org/10.1007/s12665-019-8385-y>) contains supplementary material, which is available to authorized users.

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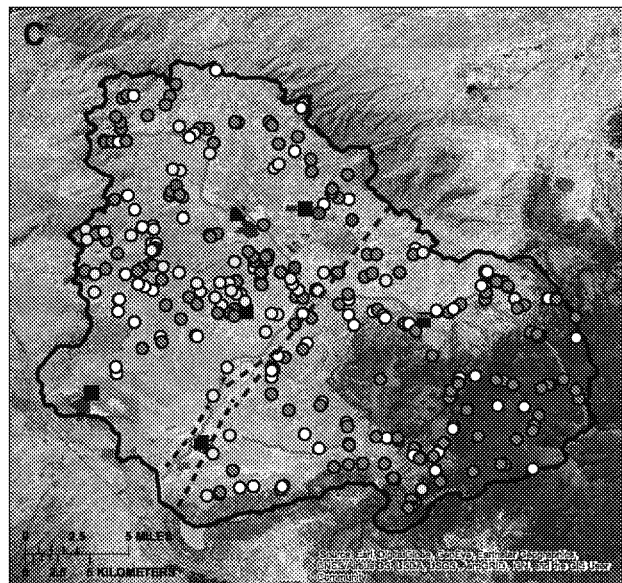
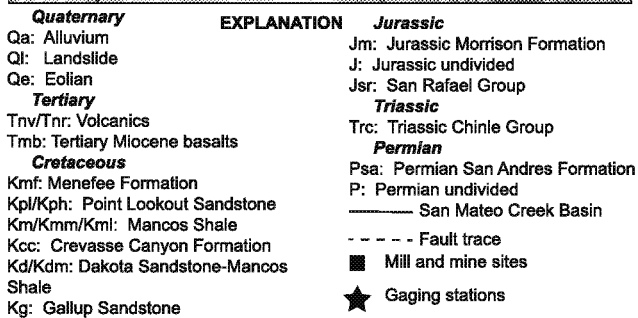
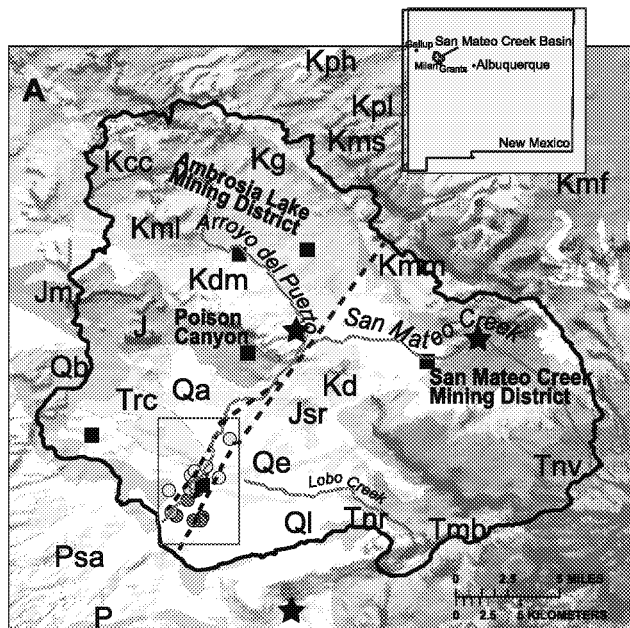
¹ U.S. Geological Survey, 6700 Edith Blvd. NE, Albuquerque, NM 87113, USA

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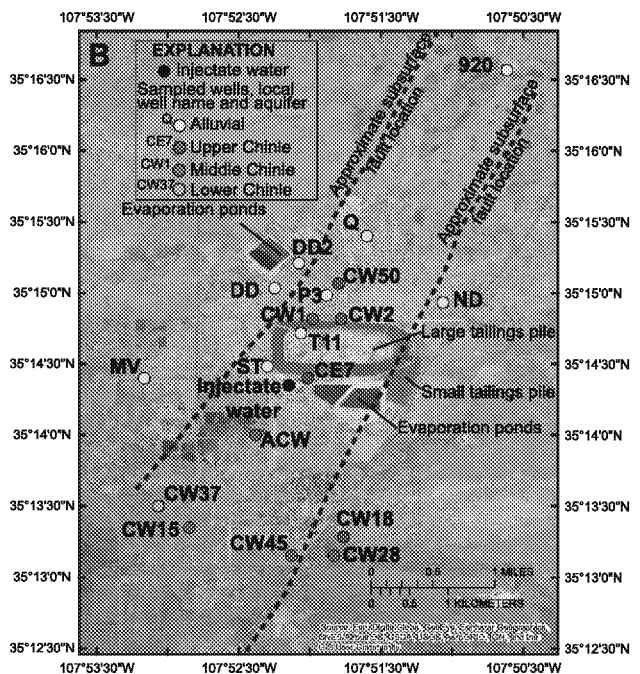
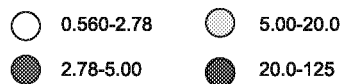
³ U.S. Geological Survey, 501 W. Felix Street Bldg 24, Fort Worth, TX 76133, USA

Introduction

Elevated concentrations of uranium (U) and co-occurring constituents, such as selenium (Se) and molybdenum (Mo), in groundwater at and surrounding the Homestake U mill site (Site) near Milan, New Mexico, USA, may originate from undisturbed ore deposits, mining activities, or milling activities from regional (within the San Mateo Creek Basin) or local (Site) sources (U.S. Environmental Protection Agency (EPA) 2011) (Fig. 1a, b). Dewatering of uranium mines in the San Mateo Creek mining district and the Ambrosia Lake mining district, both located in the San Mateo Creek Basin (Fig. 1a), led to contamination of downgradient sediment, alluvial aquifers, and deeper Chinle Group aquifers. Recharge to the deeper aquifers occurs via faults and subcropping of the Chinle Group strata beneath



NURE Sediment Uranium Concentrations (mg/kg)



Homestake Mill within the San Mateo Creek Basin

Insert from A that is shown in B

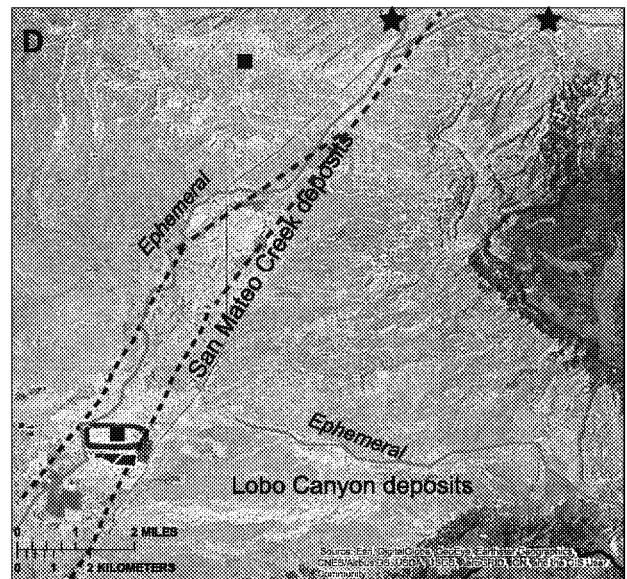


Fig. 1 Map of the Site within New Mexico and the San Mateo Creek Basin. **a** Geology from NMBGMR (2003). **b** Aerial image of the Site with well spatial locations and formation type. **c** Aerial image of the San Mateo Creek Basin with NURE sediment concentration data. **d** Aerial image of the two main drainages into the Site, the San Mateo Creek and Lobo Canyon. Well names used in this study are those defined by the Site managers

the alluvium in the area (Gallaher and Goad 1981; Schoeppner 2008). The Chinle Group aquifers are near the surface in areas to the south and west of the Site and dip close to vertical beneath the alluvium. The alluvial aquifer was recharged as the mine water was discharged into natural waterways without treatment (Langman et al. 2012). In addition, there are two tailings piles, large and small (Fig. 1b), located on the Site, where infiltration or runoff may affect the water quality in underlying/adjacent aquifers. Uranium and Mo are considered the most mobile constituents of concern from U mill sites and Se is often associated with U ore (Morrison and Spangler 1992). Gallaher and Cary (1986) suggest that impacts of mine dewatering are evident by Mo concentrations in alluvial groundwater greater than 30 µg/L, U concentrations greater than 100 µg/L, changes in total dissolved solids (TDS), and changes in major water chemistry. Signatures of contaminants are evidenced by elevated concentrations in Mo, U, or Se at the near surface that decreases with depth. Selenium concentrations in sediments related to the Poison Canyon area are generally high (Gallaher and Cary 1986). The range of Se concentration in U ore in the Grants Mineral Belt, which includes the San Mateo Creek Basin, is 200–700 mg/kg (Brookins 1977).

Site cleanup standards are based on a local assessment of background concentrations of contaminants. The drinking water standard established by the EPA for U is 30 µg/L (EPA 2017). Groundwater samples categorized as background samples for this Site had levels of U exceeding this drinking water standard (Homestake Mining Company and Hydro-Engineering, LLC 2014). Uranium concentrations in the background samples were likely affected by pervasive mining activities in the basins upgradient of the mill site, and there is potential for regional contamination to impact local water quality (Homestake Mining Company and Hydro-Engineering, LLC 2014). Regional U concentrations in groundwater from the San Mateo Creek Basin were measured from < 10 to 500 µg/L (New Mexico Environment Department, NMED 2012). Based on the background data, the EPA, NMED, and the Nuclear Regulatory Commission set the cleanup standard of U at 160 µg/L in the alluvial aquifer (Agency for Toxic Substances and Disease Registry, ATSDR 2009; Homestake Mining Company and Hydro-Engineering, LLC 2014). Because groundwater recharges from the alluvium to the underlying Chinle Group aquifer through subcropping strata, a similar standard is being applied to parts of the Chinle Group (Homestake Mining

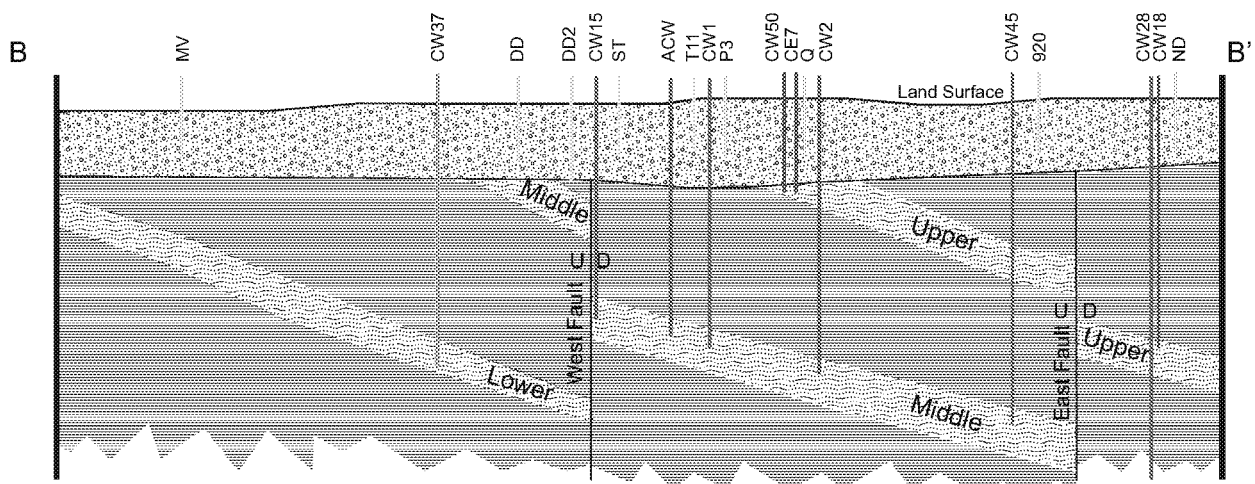
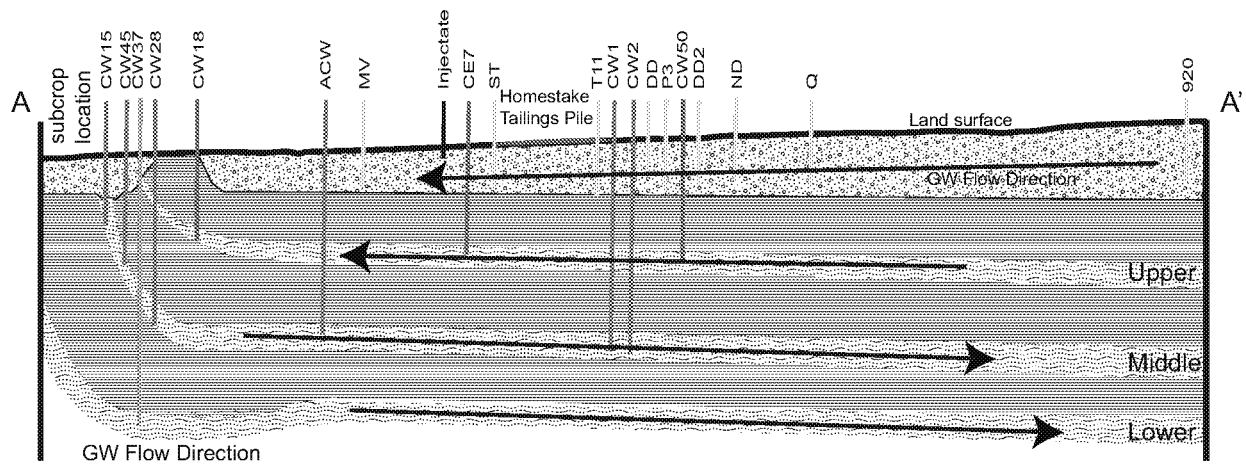
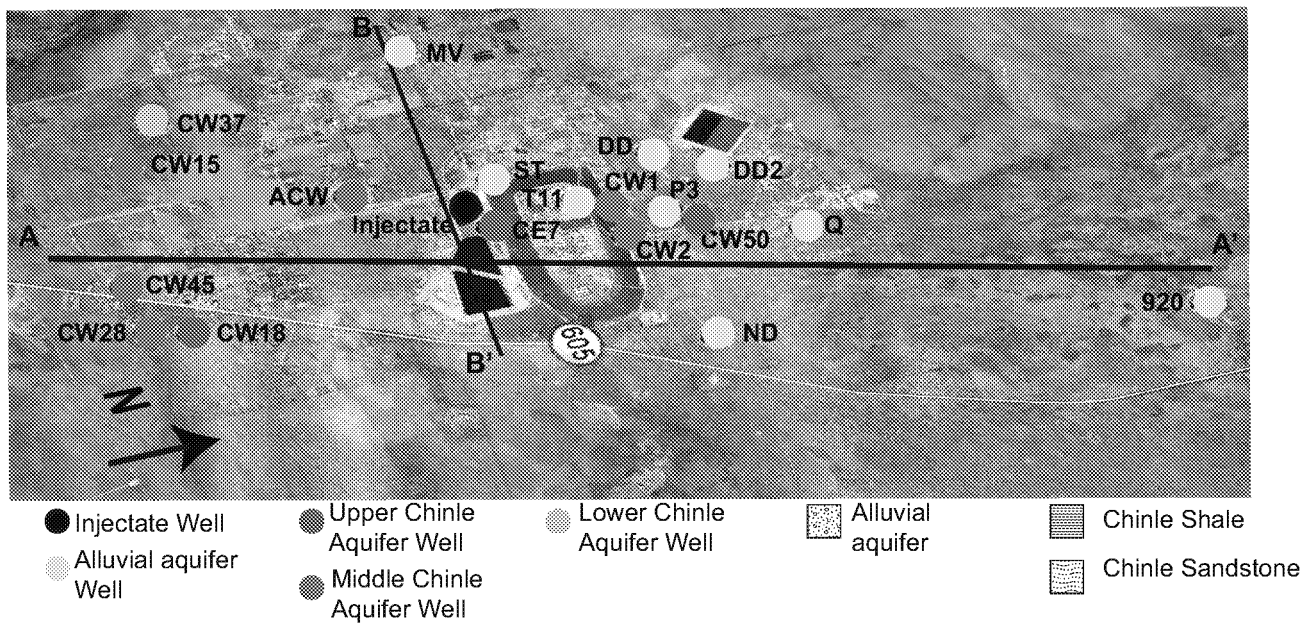
Company and Hydro-Engineering, LLC 2004). The areas of the Chinle Group aquifer in which the chemical composition of water has been altered by inflow of alluvial water are designated as the mixing zone, and have a cleanup standard of 160 µg/L U; parts of the formation in which the chemical composition of water has not been altered by inflow of alluvial water are designated as the non-mixing zone and have a different cleanup standard (Homestake Mining Company and Hydro-Engineering, LLC 2004).

The main objective of this paper is to differentiate the water type and source of U in groundwater in wells at and near the Site as either (1) sourced regionally from upgradient mining, (2) sourced locally by the mill Site, (3) sourced from deeper groundwater from the Chinle Group aquifer, and (4) sourced through other mechanisms such as upwelling from faults or mobility from surficial sediments. Water type and U source were determined using a geochemical fingerprinting approach of well-to-well variability and end-member variability. Multiple lines of evidence, including general chemistry, stable isotopes, radiogenic isotopes, borehole geophysics, groundwater age dating, and multivariate statistics were used to differentiate sources of water and specifically sources of U in the groundwater.

Geological setting and site description

The geology, hydrogeology, and hydrogeochemistry in the area are complex (Langman et al. 2012; Gallaher and Goad 1981). Numerous faults near the Site may affect the groundwater hydrogeology and geochemical interactions. In addition, the Chinle Group hydrogeologic units subcrop south of the Site (Fig. 2). Passive sampling of select wells in the area combined with spectral gamma-ray results indicate that alluvial aquifer stratigraphy and long screens in the monitoring wells play a role in degree of mixing in each well (Harte et al. 2019). The complexities of the site require rigorous analysis afforded by statistical techniques and multiple lines of evidence.

The Grants Mineral Belt is a southeast-trending zone of U deposits along the southern margin of the San Juan Basin in New Mexico (Brookins 1977). There are several mine and mill locations within the San Mateo Creek Basin, where the Site is located (Fig. 1a). The Site, north of Milan, New Mexico in the lower San Mateo Creek Basin, opened in 1958 and closed in 1990 (ATSDR 2009). The mill operations used an alkaline leach–caustic precipitation process to concentrate U from the ores (ATSDR 2009), using sodium carbonate and sodium bicarbonate (Nuclear Regulatory Commission 1981). Currently (2019), there are large and small tailings piles from mill processing and several evaporation ponds at the Site (Fig. 1b). As previously mentioned, these tailings sit atop an alluvial aquifer, which is underlain by the Upper, Middle, and Lower Chinle Group aquifers. Well names used



Conceptual models- not to scale

Fig. 2 Aerial image of the Site with well spatial locations, formation of completion, and cross-sectional locations. Cross sections A–A' and B–B' are shown below the aerial image. Arrows show the general direction of groundwater flow. The subcrops of the Chinle Group are shown in cross section A–A'. All figures are conceptual and based upon information presented in Hydro-Engineering LLC (2001) and Homestake Mining Company and Hydro-Engineering, LLC (2004)

in this study are those defined by the Site managers. Alluvial aquifer wells have the simplest alphabetic names and Chinle Group aquifer wells start with CW or CE (Fig. 1b).

The arroyo and ephemeral stream channels in the area are Quaternary (Holocene) alluvium with sand, gravel, and silt/clay in and adjacent to modern arroyo channels. The alluvium is generally 0–10 m thick and at or near the grade of modern channels (Cather 2011). Adjacent eolian and alluvial deposits from the Upper Pleistocene–Holocene, which are older than the arroyo and ephemeral stream deposits, have surface expression near the Site, likely because of uplift and erosion over geologic time. These older deposits of eolian sand and loessic silt are 0–10 m thick and have been locally reworked by alluvial processes (Cather 2011). The San Mateo Creek sediments are younger than the underlying eolian and alluvial deposits and may affect groundwater flow and geochemical processes based on the sediment sorting, grain size, mineralogy and chemical composition. For example, where sediments are coarse, groundwater flow is enhanced, and groundwater tends to be oxic (Turner-Peterson and Fishman 1986; Brookins 1977). In contrast, in finer grained sediment, groundwater flow rates are slow and water may be chemically reducing, which can affect mobility of redox-sensitive chemical elements such as U and Se (Turner-Peterson and Fishman 1986; Brookins 1977).

Sources of uranium at the site

Surface sediments collected in the 1970s through a program called the National Uranium Resource Evaluation (NURE) (U.S. Geological Survey, USGS 2004) show the distribution of U in soil samples and stream sediments in the San Mateo Creek Basin (Fig. 1c). Based on the NURE data, the ranges of soil and sediment U concentrations in four groupings are (1) the lowest concentration reported to the crustal average of 2.78 mg/kg (EPA 2008); (2) > 2.78 mg/kg to 5.00 mg/kg; (3) > 5.00 mg/kg to 20.0 mg/kg; and (4) > 20.0 mg/kg and 125 mg/kg. The highest concentrations of U in sediment are found near the San Mateo Creek, Ambrosia Lake, and Poison Canyon mines (Fig. 1a, c). Concentrations of U in sediments in Lobo Creek are generally lower than concentrations in San Mateo Creek and Arroyo del Puerto (Fig. 1a, c, d). These channels, Lobo Creek, San Mateo Creek, and Arroyo del Puerto, flow towards the Site and may affect the chemistry of sediments and water near the Site. The confluence of San Mateo Creek and Arroyo del Puerto, both ephemeral

creeks, lies in the upper San Mateo Creek Basin north of the Site (Langman et al. 2012). From the confluence, San Mateo Creek traverses southwest directly towards the Site (Fig. 1a, d). Over 30 years ago, the San Mateo Creek channel course was changed by Homestake Mining Company to flow to the west of the Site (Roca Honda Resources, LLC 2011); however, there is still a surface expression of the original channel in sediments from northeast to southwest to the north of the Site (Fig. 1d).

During active mining, mine discharge from Ambrosia Lake and San Mateo mines was directed into San Mateo Creek and Arroyo del Puerto; these ephemeral streams became perennial while mine discharge continued (Kaufman et al. 1976). There is evidence that groundwater in the area rose as much as 15 m (50 feet) from 1950 to 1980, then declined when mine discharge to the channels stopped (Weston Solutions, Inc. 2016). USGS streamgaging stations recorded discharge in the San Mateo Creek (1977–1982) and Arroyo del Puerto channels (1979–1982) above their confluence (USGS 2018) (Figure S1). Water from these channels may have infiltrated into shallow alluvial aquifers or evaporated, leaving behind constituents of concern such as U, Se, and radionuclides adsorbed or precipitated on alluvial sediments. Constituents in water that recharged the alluvial aquifer could be mobile under geochemical conditions appropriate for each constituent (NMED 2008). On the land surface, streambed sediments containing sorbed or precipitated constituents could be scoured and mobilized during larger storm events. Storm runoff could transport sediments containing mine water constituents downstream where they could be redeposited as stormflow recedes (Gallaher and Cary 1986). This process can readily occur during sporadic high-intensity rain events that occur during the summer monsoon season characteristic to this geographic area (Blake et al. 2017a).

Under current conditions, the San Mateo Creek and Arroyo del Puerto are ephemeral and further downstream, the Rio San Jose near Grants, NM, is perennial (Figure S1) (Roca Honda Resources, LLC 2011). The San Mateo Creek channel widens below the confluence with the Arroyo del Puerto, the slope of the channel decreases, and flow rarely reaches as far as a few miles past the confluence with Arroyo del Puerto (Roca Honda Resources, LLC 2011).

Water moves through the alluvium and Upper Chinle Group from northeast to southwest in the study area (Baldwin and Anderholm 1992). The general direction of flow in the Middle and Lower Chinle Group aquifers is from southwest to east and northeast and flow is down-dip (Langman et al. 2012) (Fig. 2). The dip of the Chinle Group aquifer is approximately to the north.

The Chinle Group is typically a confining unit in the area, with hydraulic conductivity values of the shale layers in the Chinle Group ranging from 10^{-1} to 10^{-8} ft/day (Baldwin

and Anderholm 1992; Baldwin and Rankin 1995). However, in between the shale layers are three layers of more coarse-grained deposits. In general, recharge to the Chinle Group aquifer is from downward leakage of water in the formation and can occur at subcrop locations (Fig. 2) (Baldwin and Anderholm 1992). There are two subsurface faults that cross the study area (Cather 2011) (Figs. 1b, d, 2). The Chinle Group aquifers are intersected by these faults that bound the overlying area of the large tailings pile. Along fault traces, permeability may be higher than in other areas (Fetter 2001), depending upon the material in the fault zone (Langman et al. 2012), resulting in a conduit for mixing between the alluvial and Chinle Group aquifers (ATSDR 2009). Groundwater mounding below the large tailings pile because of treated water injection has been reported (Home-stake Mining Company of California 2012); however, the present study did not focus on groundwater levels, but rather geochemical signatures of the groundwater.

Controls on uranium mobility

Uranium mobility is affected by redox, pH, and aqueous complexes. The insoluble form U(IV) is predominant in U ore (Brookins 1977; Hall et al. 2017) and can be oxidized in the presence of molecular oxygen or nitrate, among other constituents (Borch et al. 2010; Van Berk and Fu 2017). Once U(IV) solids are exposed to oxygen and oxidized during mining or milling, the oxidation state becomes U(VI) (Basu et al. 2015), which is mobile in water. In addition, abiotic and biotic nitrate reduction (denitrification) reactions may produce intermediates such as nitrite and nitrous oxide that will abiotically oxidize U(IV) to U(VI) (Nolan and Weber 2015; Senko et al. 2002). Microbial denitrification can be identified with stable isotopes of nitrogen and oxygen, where $\delta^{18}\text{O}$ -nitrate vs $\delta^{15}\text{N}$ -nitrate has a linear relation and high positive slope (Basu et al. 2015; Bottcher et al. 1990).

The dominant form of U adsorbed to sediments under oxidizing conditions is the uranyl ion, $(\text{UO}_2)^{2+}$ (Alam and Cheng 2014). In the presence of high carbonate concentrations in water and at pH of 6 and higher (Dong and Brooks 2006), uranyl ion–calcium–carbonate aqueous complexes are formed, which mobilizes U(VI) from sediments into water (Leavitt et al. 2011; Briganti et al. 2017). These reactions governing U mobility are potential transport and distribution pathways of U as a contaminant of concern.

Geochemical fingerprints

Geochemical constituents in groundwater that has recharged from the surface evolve due to interaction with rocks and sediments along the groundwater flow path. Geochemical

fingerprints expressed as major ion composition, U isotope ratios ($^{234}\text{U}/^{238}\text{U}$), radium isotopes (^{226}Ra and ^{228}Ra), radon concentrations (Rn), sulfur isotopes ($\delta^{34}\text{S}$), and stable isotopes of water [oxygen ($\delta^{18}\text{O}$) and hydrogen (δD)] can help to understand the type of water and source of U in groundwater (Basu et al. 2015; Yabusaki et al. 2007; Christensen et al. 2004; Zielinski et al. 1997).

The U activity ratio (UAR) of $^{234}\text{U}/^{238}\text{U}$ can indicate the origin of groundwater (Kamp and Morrison 2014). The ^{234}U isotope is a daughter of the ^{238}U isotope and when the UAR is equal to 1, the isotopes have reached secular equilibrium, and the activities are equal. U isotopes reach secular equilibrium in approximately 1 million years. Because the ore deposits in the area are older than 1 million years, the ore bodies are likely in secular equilibrium, and water with U derived from contact with mine tailings or mill sites should have a UAR equal to 1 (Corcho et al. 2015). The UAR of two discharge effluent samples collected in 1990 from the San Mateo Mine are reported as 1.06 and 1.07 (Van Metre et al. 1997). Additionally, the milling process completely dissolves the U ore minerals, which results in a theoretical UAR value of around 1–1.3 in the groundwater affected by the milling (Kamp and Morrison 2014). A UAR greater than 1 may indicate water unaffected by mine or mill tailings. For example, the UAR from samples in bedrock wells of the Dakota and Morrison Formations, thought to be unaffected by mining in the area, ranged from 2.0 to 6.7 (Van Metre et al. 1997).

Radium (Ra) isotopes and radon (Rn) concentrations in groundwater can indicate interaction with material from mines or mills. For instance, ^{226}Ra (a daughter product of radioactive decay of ^{238}U) concentrations tend to increase near ore bodies (Kaufman et al. 1976). Natural background concentrations of ^{226}Ra in the area are generally around 3 picocurie per liter (pCi/L), whereas the effluent from operating mines in the Grants Mineral Belt had ^{226}Ra concentrations of 100 pCi/L or more (Kaufman et al. 1976). Seepage from the large tailings pile had a ^{226}Ra concentration of 52 pCi/L (Kaufman et al. 1976). The range of Rn concentrations from groundwater percolating through U ore bodies can range from 2300 pCi/L to 109,000 pCi/L depending on the source of the water (Sahu et al. 2016). The Rn concentration in water can be diluted with increasing distance from the ore body (Sahu et al. 2016); however, because Rn has a half-life of 3.8 days, it does not persist far from its source and the dilution effect may be negligible.

Sulfate is a major constituent related to mine waste and mill tailings (Abdelouas 2006; Ries 1982). To differentiate between natural sulfate concentrations and concentrations related to mining or milling, stable sulfur isotopes of sulfate can be analyzed to identify the source of the sulfate (Kamp and Morrison 2014; Ries 1982). For example, $\delta^{34}\text{S}$ of sulfate values in groundwater surrounding the mill site located in

the Ambrosia Lake mining district range from -28.5 per mil (‰) to $+10.4$ ‰ (Ries 1982). Pyrite in sandstone-type U deposits in the Grants Mineral Belt has a $\delta^{34}\text{S}$ range of -27 ‰ to -1.8 ‰ (Jensen 1963). For the Faith Mine ore, located in Poison Canyon, $\delta^{34}\text{S}$ is equal to -27.2 ‰ and the $\delta^{34}\text{S}$ range identified from water in tailings ponds and groundwater near U mill sites in the Grants Mineral Belt and Navajo Nation is -5 ‰ to 5 ‰ (Kamp and Morrison 2014).

As relatively conservative isotopes, isotopic ratios of oxygen ($\delta^{18}\text{O}$) and hydrogen (δD) are not altered on contact with organic or geologic materials (Kendall and Caldwell 1998), which make them good chemical tracers of recharged water. However, the isotopes are affected by mass-dependent fractionation, which manifests as differences in physical and chemical properties based on the mass differences (Kendall and Caldwell 1998). These differences are related to temperature changes during precipitation and evaporation of water (Ingraham 1998) and occur during atmospheric exposure. Once precipitation enters the ground beyond the zone of evaporation, the isotopic signature is fixed. Stable isotopes δD and $\delta^{18}\text{O}$ can be indicative of recharge temperatures, evaporation, or upwelling from deep aquifers (Ingraham 1998; Robertson et al. 2016).

Conceptualization of U sources

Identifying the source of U at a site can be complex, especially in a location with multiple potential anthropogenic and natural sources. At this Site, there are four water sources defined: (1) regionally sourced from mining to the north of the Site; (2) locally sourced by the mill Site; (3) sourced from a deeper aquifer; and (4) other. Within each source, there is the potential for regional and local differences including contaminated and uncontaminated wells, natural heterogeneity, and differences in aquifers. The variability among the individual wells may be associated with the lithology, hydrogeology, or spatial location, which may be seen in Figs. 1 and 2. The specific geochemical signatures of each well were used to understand the general source water. Statistical analyses were used to narrow down the most appropriate geochemical signatures for this Site. Table 1 identifies the geochemical signature, description of the results that aid in identifying water source and relation to mining, and the associated figure in the text. In some cases, there may be more than one water source to a well.

Methods

Groundwater samples were collected from twenty wells both distal and proximal to the Site for an array of chemical constituents (Figs. 1b, 2; Blake et al. 2017b; Harte et al. 2018b) to help delineate chemical signatures associated with

the water sources in the area. A combination of monitoring wells, existing remedial extraction wells, and residential wells was sampled. Wells are screened in alluvium and in the Upper, Middle, and Lower Chinle Group aquifers. The injectate is water pumped from the tailings pile, treated in the reverse osmosis plant at the Site, and mixed with water from the San Andres-Glorieta Formation aquifer prior to injecting into the subsurface (Homestake Mining Company and Hydro-Engineering, LLC 2014) (injectate; Figs. 1b, 2). Groundwater-quality sampling followed volumetric purging procedures as outlined in the USGS National Field Manual (USGS 2006). Details of sampling, collection, preservation techniques, and chemical analyses are included in the Supplementary Information (SI).

Three multivariate statistical techniques, principal component analysis (PCA), non-metric multidimensional scaling (NMDS), and cluster analysis were used to quantitatively investigate the similarities and differences in groundwater geochemistry in the wells (de Carvalho Filho et al. 2017; Jiang et al. 2015). Details of these techniques are included in the SI.

For this study, the following constituents were used as input for the PCA, NMDS, and cluster analysis: gross alpha, gross beta, ^{226}Ra , ^{228}Ra , ^{234}U , ^{238}U , uranium concentrations, alkalinity, calcium, iron, magnesium, chloride, sulfate, sodium, molybdenum, and vanadium. These constituents were chosen based on the component loadings calculated from PCA when using all measured constituents. The constituents chosen had at least a 0.8 component loading when compared with all measured constituents.

Piper diagrams were created using GWChart (USGS 2015). Geochemical modeling to determine aqueous complexes and mineral saturation indices was completed in PHREEQC version 3.4.0.12927 using the minteqv4 database (Parkhurst and Appelo 1999). Major and trace element chemistry data of filtered water from each well were used as input for the model and are accessible in the corresponding data release (Blake et al. 2017b). Groundwater ages based on dating of well samples were used to calculate groundwater travel times at the Site. Details are given in the SI.

Results and discussion

Each section of the results and discussion describes the line of evidence used to identify the source of U to each well. Groups of wells with similar signatures are discussed.

Major water types

Two dominant end members in waters from the wells sampled in this study, sulfate–calcium ($\text{SO}_4\text{--Ca}$) and sulfate–sodium plus potassium ($\text{SO}_4\text{--Na + K}$), are identified in

Table 1 Geochemical signature and water source descriptions

Water source	Piper diagram (Fig. 3)	Co-constituents (Fig. 4 and S2)	PCA (Fig. 6a,b)	NMDS (Fig. 6c)	Cluster (Fig. 6d)	$^{234}\text{U}/^{238}\text{U}$ (Fig. 7a)	Radon (Fig. 7b)	Radium (Fig. 7c)	Gross alpha/beta (Fig. 7d)
1. Regionally sourced from upgradient mining	Wells that near each other have similar water types. End members and wells mixed between end members can be identified	Higher U concentration, likely closer to source. High TDS may indicate mining or mill source	Wells that plot near each other may have the same or similar water sources	Wells that plot near each other may have the same or similar water sources	Wells that plot near each other may have the same or similar water sources	UAR = 1, mining or mill tailings signature. UAR > 1.3 may not be affected by mining or mill tailings. UAR between 1 and 1.3 may show mixing	High radon may be associated with inputs from faults or proximity to uranium source	High Ra concentrations may indicate proximity to source	High Gross Alpha may show wells with radioactive sediments
1a. San Mateo Creek Channel (Fig. 1d): wells within the channel may be affected by mine discharge and adsorption or precipitation on sediments	Wells that near each other have similar water types. End members and wells mixed between end member can be identified	Higher U concentration, likely closer to source. High TDS may indicate mining or mill source	Wells that plot near each other may have the same or similar water sources	Wells that plot near each other may have the same or similar water sources	Wells that plot near each other may have the same or similar water sources	UAR = 1, mining or mill tailings signature. UAR > 1.3 may not be affected by mining or mill tailings. UAR between 1 and 1.3 may show mixing	High radon may be associated with inputs from faults or proximity to uranium source	High Ra concentrations may indicate proximity to source	High Gross Alpha may show wells with radioactive sediments
2. Locally sourced by the mill Site	Wells that near each other have similar water types. End members and wells mixed between end members can be identified	The subcrop area may allow for mixing from the Site to the Chinle Group aquifer	Wells that plot near each other may have the same or similar water sources	Wells that plot near each other may have the same or similar water sources	Wells that plot near each other may have the same or similar water sources	UAR = 1, mining or mill tailings signature. UAR > 1.3 may not be affected by mining or mill tailings. UAR between 1 and 1.3 may show mixing	High radon may be associated with inputs from faults or proximity to uranium source	High Ra concentrations may indicate proximity to source	High Gross Alpha may show wells with radioactive sediments
3. Sourced from deeper aquifer groundwater	Wells that plot near each other have similar water types. End members and wells mixed between end members can be identified	The subcrop area may allow for mixing from the Site to the Chinle Group aquifer	Wells that plot near each other may have the same or similar water sources	Wells that plot near each other may have the same or similar water sources	Wells that plot near each other may have the same or similar water sources		High radon may be associated with inputs from faults or proximity to uranium source		Not a clear indicator of U source

Table 1 (continued)

Water source	Piper diagram (Fig. 3)	Co-constituents (Fig. 4 and S2)	PCA (Fig. 6a,b)	NMDS (Fig. 6c)	Cluster (Fig. 6d)	$^{234}\text{U}/^{238}\text{U}$ (Fig. 7a)	Radon (Fig. 7b)	Radium (Fig. 7c)	Gross alpha/beta (Fig. 7d)
3a. Near fault (Fig. 1b): wells close to the faults may have upwelling of water from deeper ground-water	Wells that plot near each other have similar water types. End members and wells mixed between end members can be identified	The subcrop area may allow for mixing from the Site to the Chinle Group aquifer	Wells that plot near each other may have the same or similar water sources	Wells that plot near each other may have the same or similar water sources	Wells that plot near each other may have the same or similar water sources		High radon may be associated with inputs from faults or proximity to uranium source		Not a clear indicator of U source
3b. Near Subcrop (Fig. 2): potential for mixing between alluvial and Chinle aquifers	Wells that plot near each other have similar water types. End members and wells mixed between end members can be identified	The subcrop area may allow for mixing from the Site to the Chinle Group aquifer	Wells that plot near each other may have the same or similar water sources	Wells that plot near each other may have the same or similar water sources	Wells that plot near each other may have the same or similar water sources		High radon may be associated with inputs from faults or proximity to uranium source		Not a clear indicator of U source
4. Other sources	Well fits more than one category or final category is unclear	Well fits more than one category or final category is unclear	Well fits more than one category or final category is unclear	Well fits more than one category or final category is unclear	Well fits more than one category or final category is unclear	UAR = 1, mining or mill tailings signature. UAR > 1.3 may not be affected by mining or mill tailings. UAR between 1 and 1.3 may show mixing	Well fits more than one category or final category is unclear	Well fits more than one category or final category is unclear	not a clear indicator of U source

Each geochemical signature was used to interpret the source of water to individual wells

PCA principal components analysis, NMDS non-metric multidimensional scaling

the Piper diagram (Fig. 3). End member 1, $\text{SO}_4\text{--Ca}$, is similar to mine water discharge from the Arroyo Puerto Mine in the Ambrosia Lake mining district (Gallaher and Cary 1986). The alluvial aquifer wells DD, DD2, P3, 920, and Q plot in this area. These wells are within the San Mateo Creek channel and may indicate an influence from a water source to the north.

End member 2, $\text{SO}_4\text{--Na} + \text{K}$, is more dominant in groundwater from the Middle Chinle Group aquifer than from the alluvium at the Site. However, groundwater from the large tailings pile (well T11) also plots in end member 2. This may confirm that well T11 is drilled into the Chinle Group aquifer. Mine waters in the Grants Mineral Belt can contain higher concentrations of sodium and sulfate compared to natural waters (NMED 2008), which

may account for the higher values of these constituents in well T11. $\text{Na--SO}_4\text{--Cl}$ groundwater is commonly created by dissolution of evaporite minerals such as gypsum (CaSO_4) and halite (NaCl) (Vengosh 2003); evaporite dissolution could influence the composition of end member 2 groundwater samples. The Chinle Group is known to have gypsum deposits in some locations (Cather 2011), and the aridity of the region may cause evaporite or salt deposits in the alluvium. Evaporite crystals have been observed in sediments along the Rio San Jose, which flows through the Grants Mineral Belt (Popp et al. 1983). Wells that plot between the two end members in Fig. 3 vary in aquifer type and spatial location, which further demonstrates the complexity of groundwater source and composition in wells at this site.

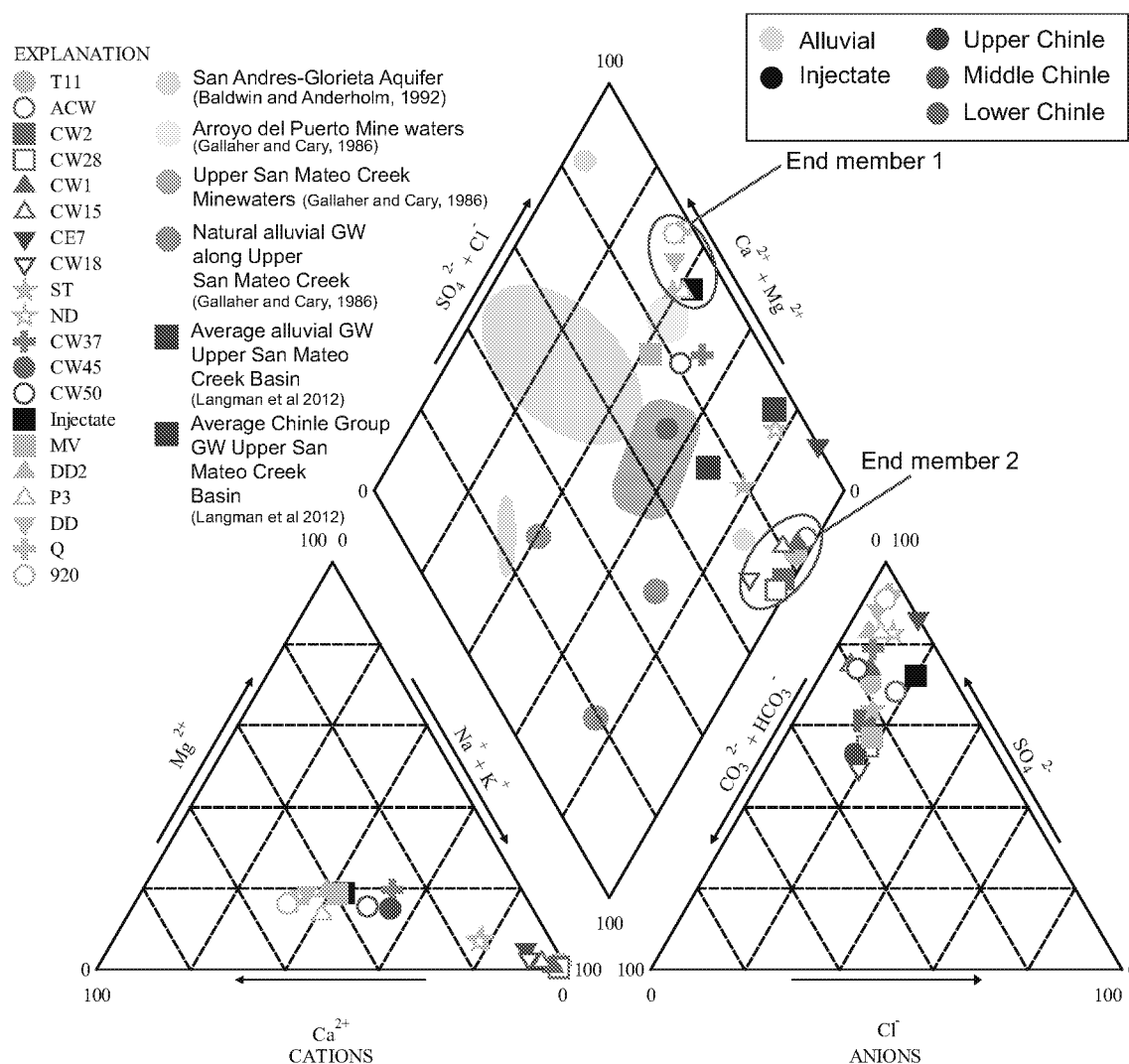


Fig. 3 Piper diagram of groundwater chemistry from wells sampled for this study. Regional groundwater data are included for comparison

Uranium, selenium, and molybdenum concentrations in groundwater

Uranium concentrations in water samples from the Site fall into three broad categories: (1) less than the drinking water standard of 30 $\mu\text{g/L}$ ($n=3$), (2) from 30 to 100 $\mu\text{g/L}$ ($n=9$), and (3) greater than 100 $\mu\text{g/L}$ ($n=8$). Uranium concentrations in groundwater collected from the Site range from 25.0 to 22,700 $\mu\text{g/L}$ (Fig. 4a, b) as reported in Harte et al. (2018a). The three highest dissolved U concentrations were measured in wells within and directly south of the large tailings pile [Chinle Group aquifer: CE7 (22,700 $\mu\text{g/L}$), Alluvial aquifer: T11 (10,029 $\mu\text{g/L}$), and ST (2709 $\mu\text{g/L}$)] and the three lowest U concentrations were measured in ND (25.0 $\mu\text{g/L}$), P3 (26.0 $\mu\text{g/L}$), and CW18 (28.0 $\mu\text{g/L}$), which are not spatially adjacent to each other. The higher U concentrations in CE7, T11, and ST were expected based on historical data and proximity to the U milling operations. Alluvial wells 920, DD2, DD, T11, MV, ST, and Chinle Group wells CE7 and CW45 have U concentrations greater than 100 $\mu\text{g/L}$, which could indicate a source from mining or milling. Given the proximity of alluvial wells 920, DD2, DD, and MV to the San Mateo Creek channel (Fig. 1a, b), these U concentrations may indicate an effect from mine dewatering. The dewatered mine water recharged the alluvium north of the Site from the upper San Mateo basin. Sediments transported in the San Mateo Creek channel from north to south contained potentially higher U source concentrations. If the dewatered mine water encountered subsurface reducing conditions, U would precipitate out of solution, and could serve as a source of U if exposed to oxic conditions. Wells T11, ST, and CE7 are adjacent to the tailings pile and water in these wells may be affected by activities at the Site. Water from well CW45 may reflect mixing with the alluvial aquifer due to its proximity to the subcrop area (Fig. 2).

Well DD ($U=103 \mu\text{g/L}$), which is spatially adjacent to well DD2, has a U concentration less than half of the concentration of DD2 ($U=250 \mu\text{g/L}$). The western fault at the Site is closer to DD2 than to DD (Figs. 1b, 2), and upwelled water from the fault may contribute to water in DD2. Well DD2 is drilled approximately 3 m (10 ft) into the upper Chinle Group Shale and is partially screened in the Chinle Group Shale. Wells DD and DD2 are adjacent to the western evaporation ponds, which may have an effect on the U concentrations in these wells, although leakage was not considered because the evaporation pond was reported to be lined (Homestake Mining Company and Hydro-Engineering, LLC 2014). Further evaluation of leakage from the evaporation pond may be beneficial.

The concentration of Se and Mo vary among the wells. The EPA drinking water standard for selenium is 50 $\mu\text{g/L}$ and the highest concentration of Se was in well CE7 (900 $\mu\text{g/L}$; Fig. 4a, c). Wells Q, P3, and 920 (Fig. 4a, c)

also had elevated Se concentrations (470, 300, and 290 $\mu\text{g/L}$, respectively). Selenium concentrations in sediments related to the Poison Canyon area are generally high (Gallagher and Cary 1986), and these sediments could be the source of elevated Se in the wells upgradient from the Site. The average Se concentration in discharge to the San Mateo Creek drainage from the Ambrosia Lake Mining District was 240 $\mu\text{g/L}$ (Gallagher and Cary 1986). Well DD has a Se concentration 33 times higher than that found in well DD2. This result may be explained by proximity to Poison Canyon, mixing from the middle Chinle Group aquifer waters, and/or mixing with groundwater from the nearby fault.

Wells CE7, T11 and ST have the highest concentrations of Mo, at 28,000, 22,000, and 3500 $\mu\text{g/L}$, respectively, which follows the same pattern as the elevated U concentrations (Fig. 4b, c) and may be explained by the fact that U and Mo are often the most mobile elements associated with U mills (Morrison and Spangler 1992). Well CW18 may have a different source of the elevated Mo due to the higher concentration compared to nearby wells.

In addition to U or Mo concentrations, total dissolved solids (TDS) may be indicative of U source water or mixed water. For instance, the average TDS concentration in alluvial groundwater upgradient of the San Mateo Creek mine was 400 mg/L (Brod and Stone 1981) and the average TDS in alluvial groundwater north of Arroyo del Puerto, in the Ambrosia Lake mining area, was 5900 mg/L (Brod and Stone 1981). Additionally, the average TDS concentration in alluvial groundwater below the confluence of Arroyo del Puerto and San Mateo Creek was 2000 mg/L (Kaufman et al. 1976) (Figure S2). The TDS concentrations from the alluvial wells sampled for this study range from 2000 mg/L (ND) to 7500 mg/L (T11). Wells MV, P3, 920, DD2, and Q have concentrations between 2000 and 3000 mg/L and wells DD and ST both have TDS concentrations of 3700 mg/L (Figure S2). These results suggest that wells north of the Site may have mine discharge water associated with them. The similarity of TDS in groundwater from well DD and ST may suggest that well DD has water from the upgradient evaporation pond seeping into the groundwater or water from the large tailings pile being transported in groundwater to the well.

Uranium mobility

Geochemical modeling

Geochemical modeling results show that the dominant species of U in the groundwater of the sampled wells is $U(VI)$, which is typical of the species related to surface mining and milling activities. The dominant aqueous complex is a uranyl carbonate, which suggests that U in groundwater is mobile. However, the presence of hydrous ferric oxides (HFO) in sediments can increase the sorption of U to

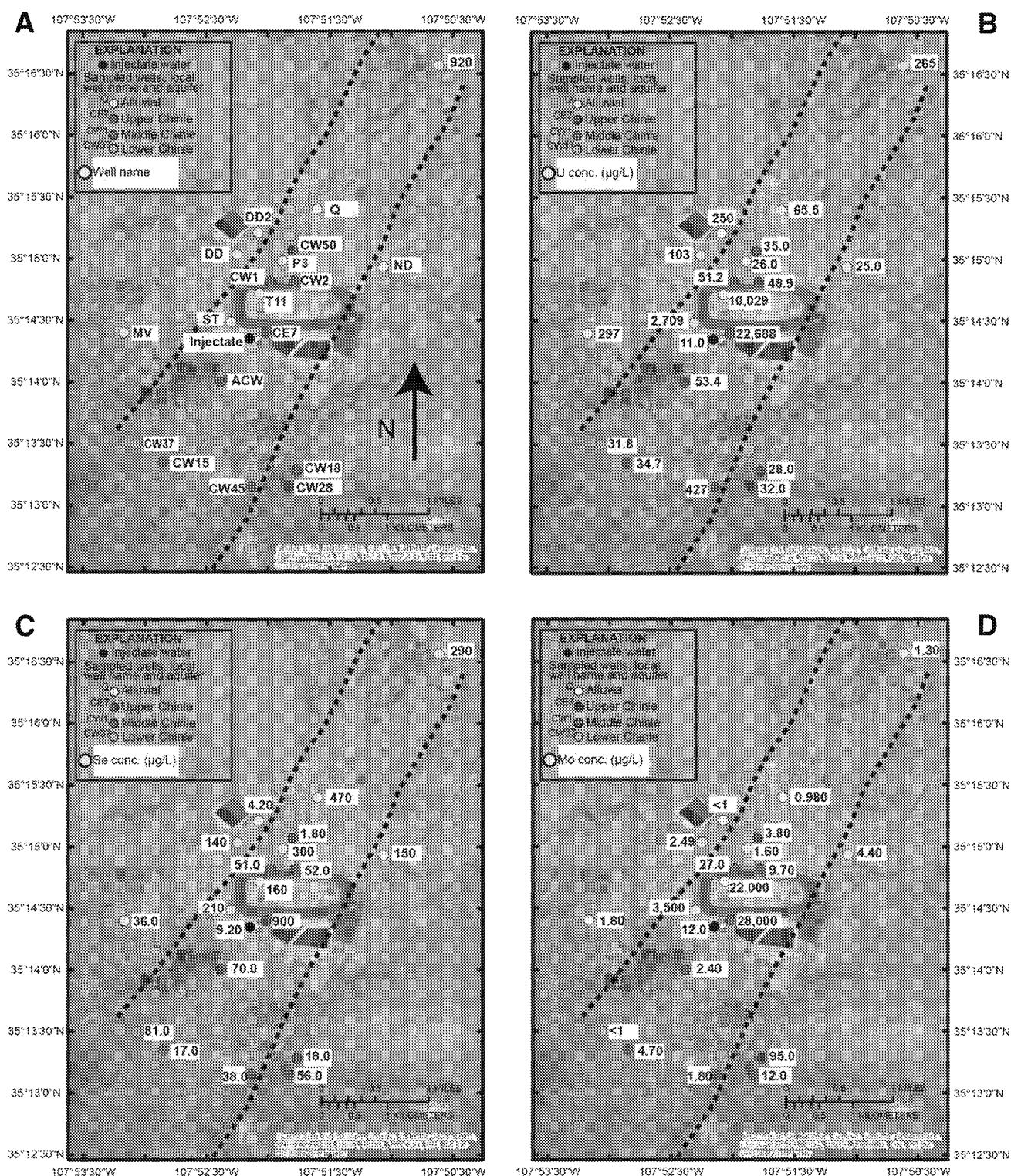


Fig. 4 Aerial photos of Site with **a** well names, **b** uranium concentrations, **c** selenium concentrations, and **d** molybdenum concentrations measured in each well at the time of sampling

sediments (Johnson et al. 2016). Harte et al. (2019) reports U spectral gamma spikes in some red clays at the Site, which are likely associated with HFOs. Water in all the samples

were supersaturated with respect to the HFOs ferrihydrite ($(\text{Fe}^{3+})_2\text{O}_3 \cdot 0.5\text{H}_2\text{O}$), goethite ($\text{FeO}(\text{OH})$), and lepidocrocite ($\gamma\text{-FeO}(\text{OH})$).

Nitrogen isotopes and redox

The comparison of $\delta^{18}\text{O}$ -nitrate vs. $\delta^{15}\text{N}$ -nitrate for the alluvial groundwater and Chinle Group groundwater shows that the alluvial groundwater has the signature of isotope fractionation related to denitrification, a relation of 1:~2 (Bottcher et al. 1990) (Fig. 5). The alluvial groundwater relation is 1:2.3 (Fig. 5) and the Chinle Group wells do not have the 1:2.3 relation suggesting that denitrification does not affect the Chinle Group wells. Denitrification reactions can produce intermediates such as nitrite and nitrous oxide that will abiotically oxidize U(IV) to U(VI), which could be the case in the alluvial aquifer (Nolan and Weber 2015; Senko et al. 2002). In addition, based on data presented in Bottcher et al. (1990), the alluvial and Chinle Group wells with lower $\delta^{18}\text{O}$ -nitrate and $\delta^{15}\text{N}$ -nitrate values (P3, ND, and CW37) may be affected by nitrogen fertilizers.

Multivariate statistics

PCA, NMDS, and cluster analysis were used to identify important geochemical fingerprints for further evaluation. Principal component 1 (PC1) accounts for 65.45% of the variance in this dataset and principal component 2 (PC2) accounts for 19.56% of the variance (Fig. 6a, b). Constituents with the highest loadings for PC1, which suggests that these constituents account for the major differences among the geochemistry of the wells, based on the PCA include SO_4^{2-} , Gross beta, ^{228}Ra , U, ^{238}U , ^{234}U , ^{235}U , gross alpha, Mo, Cl, and Na (Fig. 6a). Constituents with the highest loadings for PC2 include Fe, Ca, and Mg, which suggests that these constituents have a secondary effect on the variance in geochemistry among the wells. The distribution of the wells in the plot describes the variability in each well and

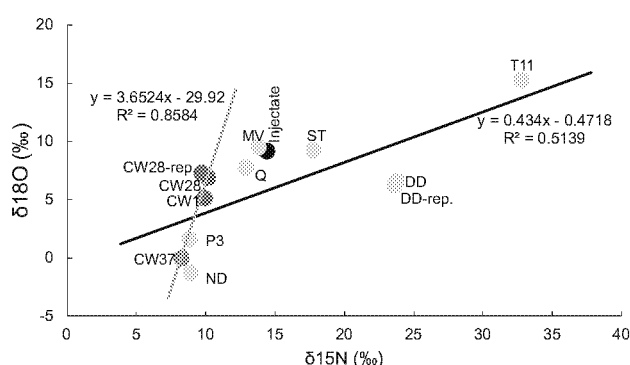


Fig. 5 Plot of $\delta^{18}\text{O}$ -nitrate vs. $\delta^{15}\text{N}$ -nitrate. Trendlines are plotted for alluvial aquifer wells (including injectate) and Chinle Group aquifer wells. The alluvial wells have a 1:2.3 relation between $\delta^{18}\text{O}$ -nitrate and $\delta^{15}\text{N}$ -nitrate. The Chinle Group aquifer wells do not show the 1:2.3 relation. Yellow circles are alluvial wells, green circles are Middle Chinle Group aquifer wells, orange circles are Upper Chinle Group aquifer wells, and the black circle is the injectate

how each well is associated with other wells (Fig. 6b). For instance, DD, Q, 920, and DD2 plot near each other while CE7 and T11 plot far from all other wells and outside of the 95% prediction ellipse.

The NMDS plot shows a slightly different distribution of the wells compared to the PCA results (Fig. 6c). The clearest differences are the separation of Q from the cluster with 920, DD, and DD2, and the closer distribution of CE7, ST, and T11. The NMDS solution converged after 20 iterations and the stress value was 0.0959442, which is indicative of a robust solution (Buttigieg and Ramette 2014). The cluster analysis shows similar well clusters to the NMDS analysis (Fig. 6d).

When comparing the results from PCA, NMDS, and cluster analysis, the following groups of wells consistently plot together: (1) 920, DD, and DD2; (2) CW15, CW18, ACW, CW28, CW1, CW2; and (3) injectate and ND. The following wells plot near each other in two of the three analyses: (1) CE7, ST, T11; (2) CW45, MV; (3) CW37, P3; and (4) CW50, injectate. Well Q is the only well that does not consistently plot near the other wells, which shows the chemistry is different from nearby wells.

The grouping or clustering is based on statistical comparisons, and certain trends are discernible. The most notable trend is that the local operations at the Site are identifiable at three wells (T11, ST, and CE7) proximal to the site, which relates to U mobility and large U concentrations at these sites (Fig. 4b), and no other wells are associated with this cluster. In contrast, the remaining wells are less distinct from each other and clustered into three groups. Wells proximal to the large tailings pile such as DD and DD2 tend to be associated with regional or local Site impacts.

Radiogenic fingerprints

Uranium isotope ratios

The alluvial well (T11) within the large tailings pile, and the alluvial (ST) and upper Chinle Group well (CE7) directly south of the large tailings pile at the Site, have $^{234}\text{U}/^{238}\text{U}$ activity ratios (UAR) of nearly 1 (Fig. 7a). This indicates that the groundwater in these wells has the signature of the mill tailings pile. Groundwater in wells CW45, CW50, MV, Q, P3, and 920 as well as the injectate water have UAR values between 1 and 1.3 (Fig. 7a). There is evidence that UAR values greater than 1.3 are likely unaffected by mining or mill tailings (Zielinski et al. 1997). However, there is also evidence that UAR values may be higher in groundwater in this area because of prolonged interaction with U-rich sediments (Johnson and Wirt 2009; Zielinski et al. 1997). Therefore, based on the UAR values, the wells that have UAR values between 1 and 1.3 may be affected by mining or mill tailings, may have a mix of unaffected and affected

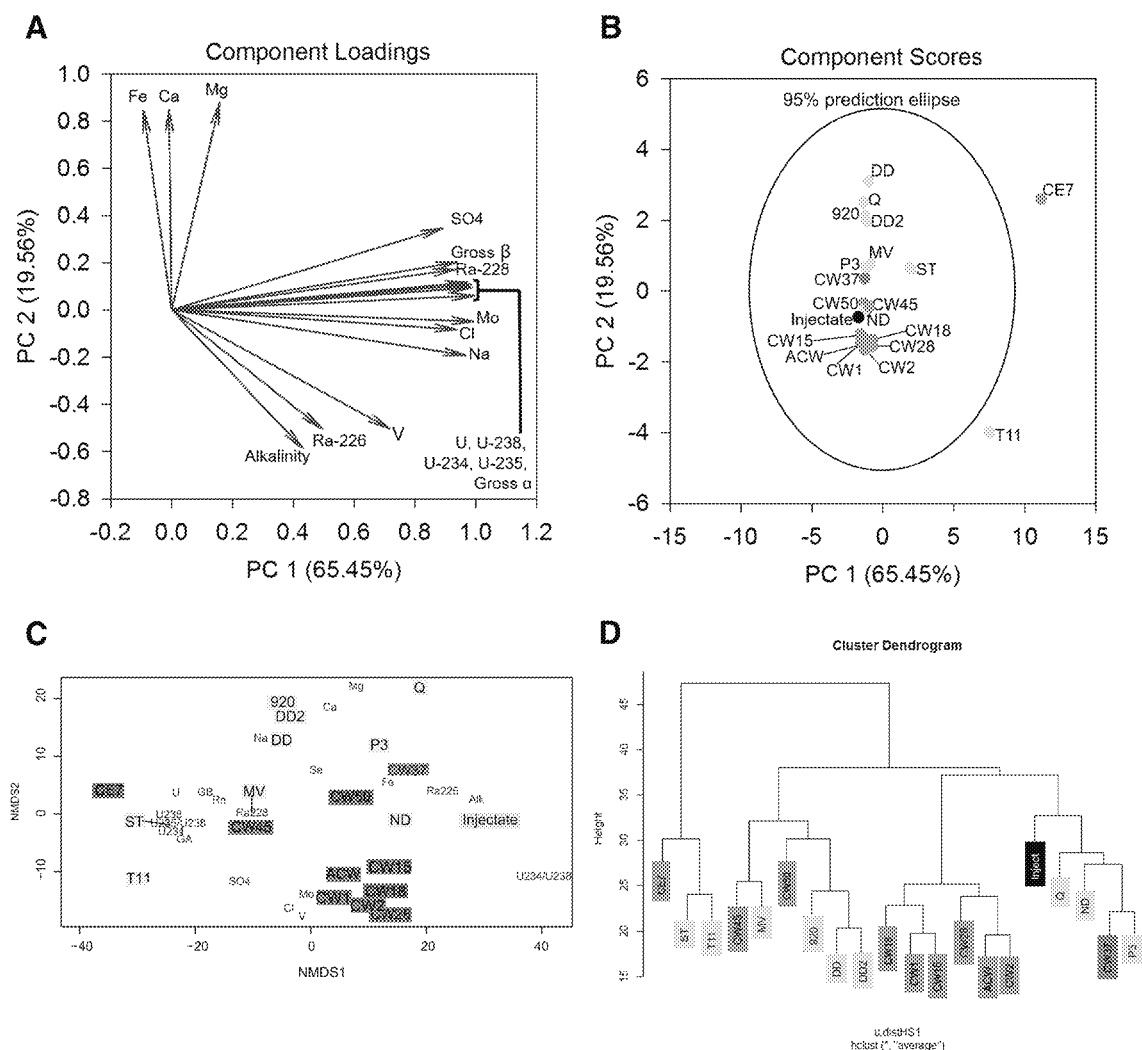


Fig. 6 Plots of multivariate statistical analyses: **a**, **b** PCA, **c** NMDS, and **d** cluster analysis

water, or may be in contact with U-rich sediments for longer periods of time.

Radon

The highest ^{222}Rn activity was found in wells DD2, CE7, T11, and CW50 (Fig. 7b). Wells CE7 and CW50 are screened in the same aquifer, the Upper Chinle Group, where the flow direction is generally from north to south under the tailings pile. Well DD2 is located adjacent to a sub-surface fault (Fig. 1b), where there is potential for ^{222}Rn to seep to the surface. Additionally, well DD2 is near the western evaporation ponds, which could be the source of the radon. T11 is in direct contact with mine tailings, which may explain the elevated ^{222}Rn activity. Radon has a short half-life (3.8 days); therefore, the water sampled from these wells must be near its source for the radon to present in high concentrations. Alternately, the high radon concentrations

may be attributed to the high concentrations of parent material (^{226}Ra) in the water.

^{226}Ra and ^{228}Ra

The distribution of ^{226}Ra and ^{228}Ra among the wells shows T11 having the highest concentration of ^{226}Ra (3.82 pCi/L) and CE7 having the highest concentration of ^{228}Ra (5.88 pCi/L) (Fig. 7c). Gallaher and Goad (1981) reported that the San Mateo area discharge from treated mine waters had ^{226}Ra concentrations of 23 ± 1 ($n=3$) pCi/L and the Ambrosia Lake discharge waters had ^{226}Ra concentrations of 4.6 ± 0.2 ($n=3$). Both reported ^{226}Ra concentrations are higher than those found in the wells sampled in this study, except for T11. Previous studies in Grants Mineral Belt streams show that ^{226}Ra generally forms insoluble precipitates or adsorbs to sediments within ten river miles of the

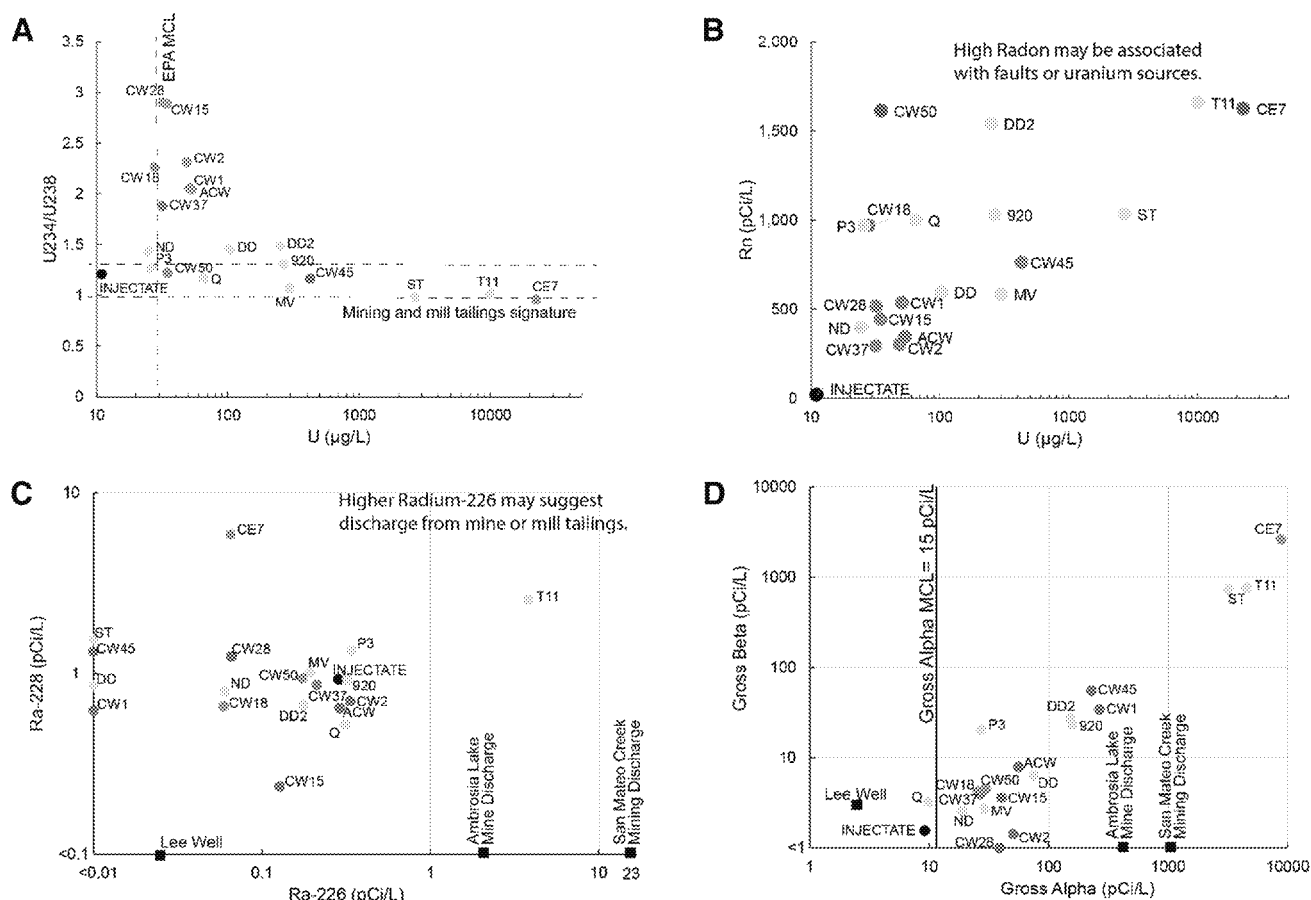


Fig. 7 Plots of **a** $^{234}\text{U}/^{238}\text{U}$ activity ratio vs. U concentration, **b** Rn concentration vs. U concentration, **c** ^{226}Ra vs. ^{228}Ra (pCi/L), and **d** gross alpha vs. gross beta

source (Gallaher and Cary 1986) and, therefore, ^{226}Ra is not found in high concentrations in groundwater in the area.

Gross alpha–beta

The gross alpha–beta results from the groundwater wells sampled reveal a distribution across the wells (Fig. 7d); eighteen of twenty wells have gross alpha values greater than the 15 pCi/L EPA MCL (EPA 2017), and CE7, ST, and T11 have the highest gross alpha–beta results. The injectate has the lowest gross alpha–beta results (Fig. 7d). Gallaher and Goad (1981) reported that treated mine effluents that discharged to San Mateo Creek and Arroyo del Puerto had gross alpha values of 1100 pCi/L ($n=3$) from the San Mateo Area and 580 ± 70 pCi/L ($n=5$) from the Ambrosia Lake area (Fig. 7d). These values are higher than the gross alpha values reported for the majority of the wells, with the exception of DD2, 920, CW1, CW45, ST, T11, and CE7. These wells with high gross alpha concentrations may have sediments with radioactive materials in contact with the water.

Stable isotopes

The stable isotopes of water (Figure S3) and sulfur (Figure S4) identify general trends of the wells. For instance, the majority of the Chinle Group wells have more negative δD and $\delta^{18}\text{O}$ values while the alluvial wells are less negative. The three wells most proximal to the large tailings have high sulfate and less negative $\delta^{34}\text{S}$ values. The alluvial wells most north of the large tailings pile have intermediate sulfate concentrations and more negative $\delta^{34}\text{S}$ values. Discussion of these trends is included in the SI.

Groundwater travel time

Groundwater travel time between wells Q and MV could be as fast as 0.30 m/day [1 ft/day (365 ft/year)] (Figure S5) as determined by the presence of environmental tracers tritium/helium and CFCs. This suggests that groundwater could travel nearly 10,000 ft (the distance between Q and MV) in 27 years. If mine water discharge in streams recharged the alluvial aquifer a few miles below the confluence of the San

Mateo Creek and Arroyo del Puerto, groundwater from this process would travel to the Site in approximately 60 years.

Source water comparisons in wells

Surface and subsurface structures near the Site reveal a complex interaction of water from mine discharge, Chinle Group and alluvial aquifer mixing and upwelling from faults, effects from the large tailings pile at the Site, and other unidentified sources. Our procedure to interpret the geochemical fingerprinting of groundwater, based on multiple lines of evidence, is shown in Table 1. Our conclusions on sources of water and U in the water are shown in Table 2.

Results suggest that alluvial wells north of the Site have fingerprints from regional sources related to upgradient mining. Alluvial wells on the western side of the Site have regionally upgradient mining water sources, signatures of the mill Site, deeper groundwater or water upwelled from faults, and potentially other sources such as the nearby evaporation ponds. The two alluvial wells closest to the large tailings pile (T11 and ST) and one Upper Chinle Group aquifer well (CE7) directly south of the large tailings pile have the most consistent fingerprints of the local mill tailings. All the deeper Chinle Group wells except two (CW1 and CW2) are mixed with alluvial water that may be affected by the Site water and deeper alluvial groundwater. Deeper groundwater and another unidentified source are the likely source of water in the alluvial well on the eastern side of the Site (ND).

The alluvial wells north of the site, 920, Q, and P3, all appear to have water sourced from regionally upgradient mining based on U concentrations, similar UAR values, and locations within the San Mateo Creek Channel, which may have legacy mining signatures associated with the sediments. Travel time calculated between Wells Q and MV based on age dating suggests that alluvial water may have had time to move the 3000 m (10,000 ft) between the wells (Figure S5; Table S2). Groundwater in wells DD, DD2, and MV not only appears to have regional mining water sources, but also show signatures of the mill Site (DD2 and MV), deeper groundwater or water upwelled from faults (DD2), and potentially

other sources (DD2 and DD) such as the nearby evaporation ponds (Fig. 1b). Water in well DD2 may be influenced by the deposition of sediments or infiltration of stream water from the San Mateo Creek channel, but also influenced by the western fault. Wells T11 and ST show the most evidence of water sourced from the mill Site on the basis of U and Mo concentrations, UAR values, and Rn concentrations. Well CE7 also shows evidence of water sourced from the mill Site, but is completed in the Upper Chinle Group aquifer, so it likely has a mixed source of water. Wells ST, T11, and CE7 are directly within or adjacent to the large tailings pile and, therefore, the gross alpha signature may be related to contact with the mill tailings.

Well ND has some geochemical similarities to alluvial wells P3, Q, and the injectate, but may be mixed with deeper aquifer water based on the Piper diagram and passive sampling results reported in Harte et al. (2019). In addition, well ND is located east of the eastern fault and within the Lobo Canyon deposits; therefore, well ND may have another source of water that is unidentified. The injectate water is known to be a mixture of reverse osmosis water and the San Andres-Glorieta Formation aquifer water.

Well CW45 is in the subcrop area at the southern edge of the Site and may be affected by alluvial waters or from upwelling from the eastern fault. Based on knowledge of the subcropped geology in the southern and western portions of the Site, it is suggested that wells CW18, CW15, CW45, ACW and CW28 are within the mixing zone between the alluvial aquifer and the Chinle Group aquifer. In addition, the wells located in the mixing zone and between the two faults, and south of the large tailings pile (ACW, CW15 and CW45) are considered affected by tailings seepage (Hydro-Engineering 2001). All of the Middle Chinle Group wells plot in the End Member 2 area of the Piper Diagram except for sampled well water from CW45, which plots in the mixed area. In addition, CW45 plots closer to MV in the NMDS biplot and the cluster analysis, which may provide further evidence of mixed water.

Well CW50 is north of the large tailings pile and in the upper Chinle Group aquifer. This well may be a mixture of

Table 2 Wells sampled in this study with their likely source(s) of water

Water source	920	Q	ND	DD2	DD	P3	T11	ST	MV	CW49	CE7	CW18	CW1	CW2	ACW	CW15	CW45	CW28	CW37	INJECTATE
1. Regionally sourced from upgradient mining	X	X		X	X	X			X											
1a. San Mateo Creek Channel	X	X		X		X														
2. Locally sourced by the mill Site				X			X	X	X	X	X	X			X	X	X	X	X	
3. Sourced from deeper aquifer groundwater			X	X						X	X	X	X	X	X	X	X	X	X	
3a. Near fault			X	X													X			
3b. Near Subcrop												X			X	X	X	X		
4. Other source			X	X	X															X

The alluvial aquifer wells are highlighted in yellow, Upper Chinle Group aquifer in blue, Middle Chinle Group aquifer in green, and Lower Chinle Group aquifer in orange. The injectate water is shown in black. Samples within each aquifer are listed from north to south

alluvial and Chinle Group water, as supported by the Piper Diagram, multivariate analysis, and UAR. Additionally, well CW50 had the highest Rn concentration of all wells, which may indicate radioactive sediments. This well is not close to either fault. Well CW37 is the only lower Chinle Group well sampled and may have a mixture of alluvial and Chinle Group water, as shown in the Piper diagram and multivariate analysis. Wells CW1 and CW2 are slightly north of the large tailings pile and are in the Middle Chinle Group aquifer. Both wells plot in End Member 2 on the Piper Diagram but have UAR values above 1.3 and low Rn concentrations, which may indicate that the water is predominantly from the Chinle Group aquifer. The Chinle Group waters with an X in the 'locally sourced by the mill Site' category in Table 2 may contain waters affected by the Site, but further study is required to identify this source.

Conclusions

The Homestake uranium mill site is a very complex hydrogeological system because of the geology, naturally occurring elements, and various anthropogenic effects at the Site and north of the Site. To understand the sources of U in each sampled groundwater well, a geochemical fingerprinting approach was used to define water sources to aid in understanding the source of U to the wells. Multiple lines of evidence, including general chemistry, stable isotopes, radiogenic isotopes, borehole geophysics, groundwater age dating, and multivariate statistics were used to differentiate sources of U and other associated compounds. This research has shown that combining geochemical fingerprinting, multivariate statistics, subsurface structure, and spectral gamma coupled with passive sampling (Harte et al. 2019) is an effective approach to understand the source of water and U in groundwater to wells nearby the Site. The multivariate statistics provided quantitative analyses of the data, which clustered wells into groups based on groundwater chemistry. The commonalities among the statistical approaches provide robust support for similarities among groundwater samples from sets of wells obtained by geochemical fingerprints.

In general, the wells proximal to the large tailings pile have the highest U concentration, Rn activity, gross alpha and beta, and UAR closest to 1. Most of the wells studied have U concentrations higher than the MCL of 30 µg/L and appear to be affected by regional sources of U. However, the injectate water, which has been treated and mixed with San Andres-Glorieta Formation aquifer groundwater, has the lowest U concentration. Geochemistry of the alluvial wells north of the Site may be influenced by San Mateo Creek channel sediments, although further analysis is needed to understand the mechanisms associated with this finding. Wells south of the Site have mixed groundwater sources,

likely because of the complexity of the hydrogeology and flow paths of groundwater in the aquifers.

The approach used in this study provides results that can be used by land managers and regulators to determine which wells best represent background concentrations for sites that have multiple effects from naturally occurring contaminants and anthropogenic contaminants. However, the data collected in this study are from one point in time. Seasonal geochemical variability was not assessed. Samples from wells reflect a mixture of water sources, partly from the installation of well screens or well openings (in open boreholes) that cross multiple types of units and formations (Harte et al. 2019). Installation of short-screen monitoring wells would help reduce mixing with the goal of collecting samples more representative of specific groundwater flow paths. Further research could include analyzing the chemistry of subsurface sediments, which could further define the geochemical interactions between these sediments and groundwater. In addition, sampling of more wells in the area, including those north of the Site, could provide information about the chemistry of the groundwater throughout the area. The results provide a new method to fingerprint groundwater and differentiate among water sources, which will aid regulators in decisions about background concentrations of U in groundwater near the Site and provide scientists with an additional geochemical fingerprinting approach.

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Message

From: Linton, Ron [Ron.Linton@nrc.gov]
Sent: 10/8/2019 12:29:11 PM
To: Purcell, Mark [purcell.mark@epa.gov]
CC: Alexander, George [George.Alexander@nrc.gov]
Subject: FW: Final Published Paper on Homestake Site Background Ground Water - Johanna Blake - USGS
Attachments: Blake 2019 EES Differentiating Anthropogenic and natural sources of U by geochemical fingerprinting of GW at the Homestake U mill (002).pdf; Homestake supplemental (002).docx

This is what you sent me. The supplemental info was in Word format, that is what gave me pause and reason to ask the question if it could go into ADAMS. The actual publication is marked as non-copyrighted, but the supplemental is not marked. I also didn't see any mention of the supplemental in the publication.

From: Purcell, Mark <purcell.mark@epa.gov>
Sent: Monday, September 23, 2019 12:22 PM
To: Tsosie, Bernadette <Bernadette.Tsosie@lm.doe.gov>; Linton, Ron <Ron.Linton@nrc.gov>; Alexander, George <George.Alexander@nrc.gov>; Kuhlman, Alison (CONTR) <Alison.Kuhlman@lm.doe.gov>
Cc: Kurt Vollbrecht (kurt.vollbrecht@state.nm.us) <kurt.vollbrecht@state.nm.us>; Longmire, Patrick, NMENV <Patrick.Longmire@state.nm.us>; Winton, Ashlynne, NMENV <Ashlynne.Winton@state.nm.us>
Subject: [External_Sender] Final Published Paper on Homestake Site Background Ground Water - Johanna Blake - USGS

All,

As discussed at our meeting in Grants last Wednesday, I have attached the final published USGS paper by Johanna Blake. Also attached is supplemental information that did not make it into the publication.

Please let me know if you have any questions or need additional information.

Mark

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Differentiating anthropogenic and natural sources of uranium by geochemical fingerprinting of groundwater at the Homestake uranium mill, Milan, New Mexico, USA

Johanna M. Blake¹ · Philip Harte² · Kent Becher³

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Abstract

A multiparameter geochemical-isotopic fingerprinting approach was used to differentiate anthropogenic and natural signatures of uranium contamination near the Homestake uranium mill site (Site), near Milan, New Mexico, USA. The Site consists of two tailings piles from milling operations and groundwater contamination from these tailings has been noted. The Site lies within the lower San Mateo Creek Basin and has multiple regional sources of uranium contamination from mining and mill operations. The Site is underlain by a heterogeneous alluvial aquifer, which is in turn underlain by basement rock of the Chinle Group aquifer and the underlying San Andres-Glorieta Formation aquifer. To help decipher signatures, several statistical approaches were used including principal component analysis, non-metric multidimensional scaling, and cluster analysis. Piper diagrams indicate two end-member water types at the Site, sulfate–Na–K generally in the Chinle Group aquifer and sulfate–Ca generally in the alluvial aquifer. There are wells from both aquifers that plot between the two end members. Uranium concentrations from the Site fall into three broad categories: less than the drinking water standard of 30 µg/L ($n=3$), from 30 to 100 µg/L ($n=9$), and greater than 100 µg/L ($n=8$). Component loadings in a principal component analysis are highest for uranium isotopes, uranium, molybdenum, chloride, sodium, ²²⁸radium, and gross alpha–beta, which affect the similarities or differences among wells sampled. Results suggest that several alluvial wells north of the Site have groundwater with anthropogenic fingerprints from regional sources related to upgradient mining. Well water with higher uranium concentrations has uranium activity ratios close to 1, which is indicative of mining or milling signatures. These same wells have elevated radon activities. This information can be used to inform Site managers regarding the source of water related to uranium at the Site and provide an approach for geochemical fingerprinting.

Keywords Geochemical fingerprint · Uranium milling · Grants Mineral Belt · ²³⁴U/²³⁸U · Multivariate statistics

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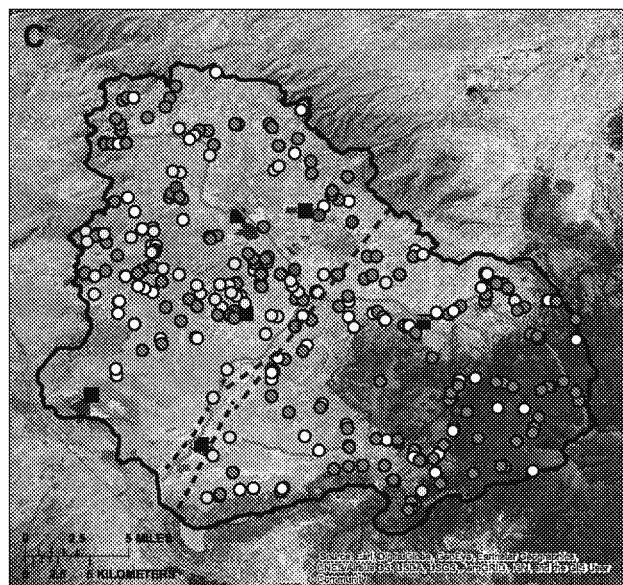
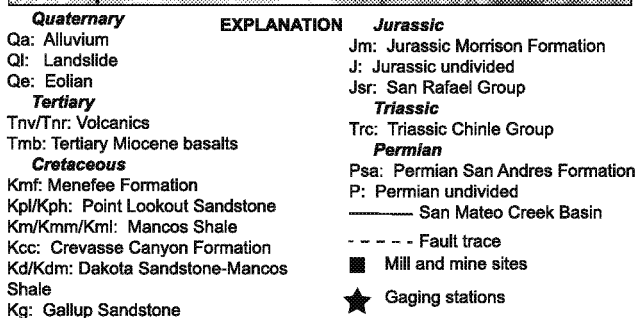
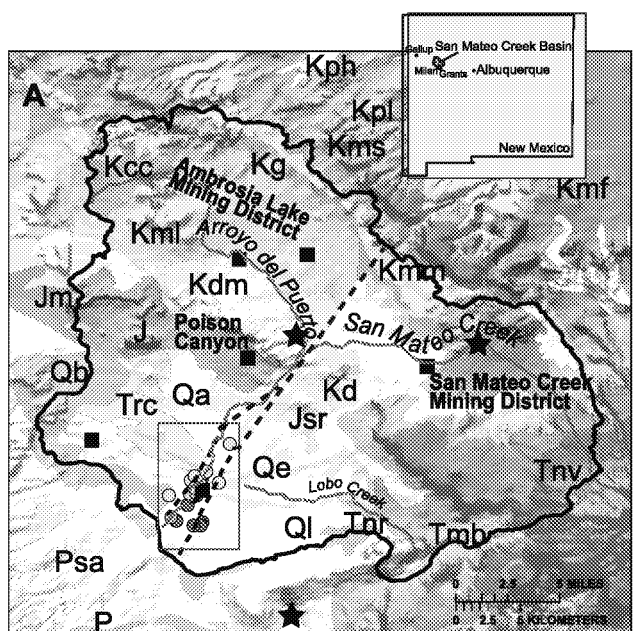
¹ U.S. Geological Survey, 6700 Edith Blvd. NE, Albuquerque, NM 87113, USA

² U.S. Geological Survey, 720 Gracern Rd, Columbia, SC 29210, USA

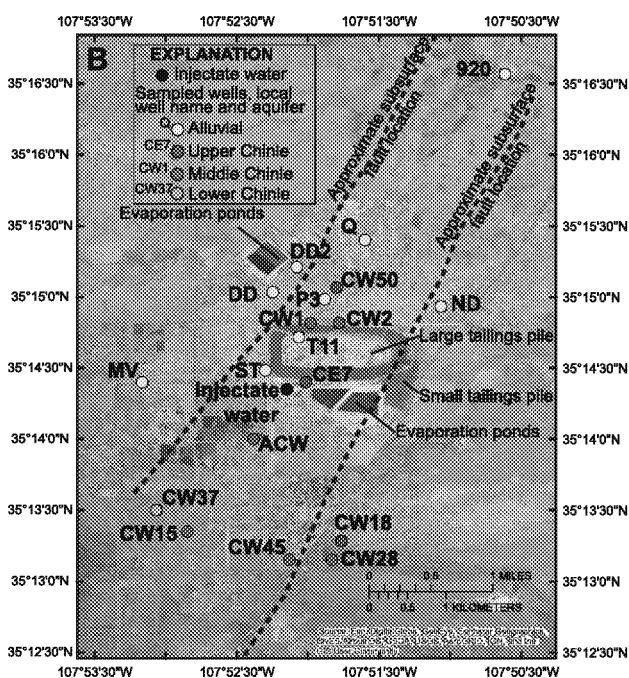
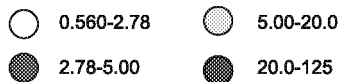
³ U.S. Geological Survey, 501 W. Felix Street Bldg 24, Fort Worth, TX 76133, USA

Introduction

Elevated concentrations of uranium (U) and co-occurring constituents, such as selenium (Se) and molybdenum (Mo), in groundwater at and surrounding the Homestake U mill site (Site) near Milan, New Mexico, USA, may originate from undisturbed ore deposits, mining activities, or milling activities from regional (within the San Mateo Creek Basin) or local (Site) sources (U.S. Environmental Protection Agency (EPA) 2011) (Fig. 1a, b). Dewatering of uranium mines in the San Mateo Creek mining district and the Ambrosia Lake mining district, both located in the San Mateo Creek Basin (Fig. 1a), led to contamination of downgradient sediment, alluvial aquifers, and deeper Chinle Group aquifers. Recharge to the deeper aquifers occurs via faults and subcropping of the Chinle Group strata beneath



NURE Sediment Uranium Concentrations (mg/kg)



Homestake Mill within the San Mateo Creek Basin



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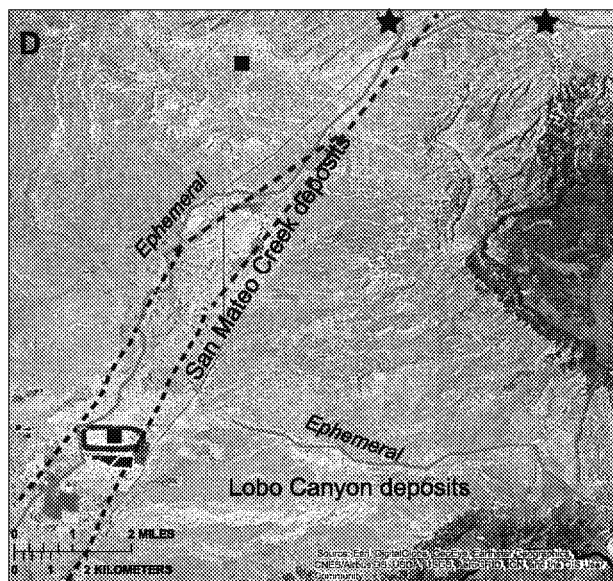


Fig. 1 Map of the Site within New Mexico and the San Mateo Creek Basin. **a** Geology from NMBGMR (2003). **b** Aerial image of the Site with well spatial locations and formation type. **c** Aerial image of the San Mateo Creek Basin with NURE sediment concentration data. **d** Aerial image of the two main drainages into the Site, the San Mateo Creek and Lobo Canyon. Well names used in this study are those defined by the Site managers

the alluvium in the area (Gallaher and Goad 1981; Schoeppner 2008). The Chinle Group aquifers are near the surface in areas to the south and west of the Site and dip close to vertical beneath the alluvium. The alluvial aquifer was recharged as the mine water was discharged into natural waterways without treatment (Langman et al. 2012). In addition, there are two tailings piles, large and small (Fig. 1b), located on the Site, where infiltration or runoff may affect the water quality in underlying/adjacent aquifers. Uranium and Mo are considered the most mobile constituents of concern from U mill sites and Se is often associated with U ore (Morrison and Spangler 1992). Gallaher and Cary (1986) suggest that impacts of mine dewatering are evident by Mo concentrations in alluvial groundwater greater than 30 µg/L, U concentrations greater than 100 µg/L, changes in total dissolved solids (TDS), and changes in major water chemistry. Signatures of contaminants are evidenced by elevated concentrations in Mo, U, or Se at the near surface that decreases with depth. Selenium concentrations in sediments related to the Poison Canyon area are generally high (Gallaher and Cary 1986). The range of Se concentration in U ore in the Grants Mineral Belt, which includes the San Mateo Creek Basin, is 200–700 mg/kg (Brookins 1977).

Site cleanup standards are based on a local assessment of background concentrations of contaminants. The drinking water standard established by the EPA for U is 30 µg/L (EPA 2017). Groundwater samples categorized as background samples for this Site had levels of U exceeding this drinking water standard (Homestake Mining Company and Hydro-Engineering, LLC 2014). Uranium concentrations in the background samples were likely affected by pervasive mining activities in the basins upgradient of the mill site, and there is potential for regional contamination to impact local water quality (Homestake Mining Company and Hydro-Engineering, LLC 2014). Regional U concentrations in groundwater from the San Mateo Creek Basin were measured from < 10 to 500 µg/L (New Mexico Environment Department, NMED 2012). Based on the background data, the EPA, NMED, and the Nuclear Regulatory Commission set the cleanup standard of U at 160 µg/L in the alluvial aquifer (Agency for Toxic Substances and Disease Registry, ATSDR 2009; Homestake Mining Company and Hydro-Engineering, LLC 2014). Because groundwater recharges from the alluvium to the underlying Chinle Group aquifer through subcropping strata, a similar standard is being applied to parts of the Chinle Group (Homestake Mining

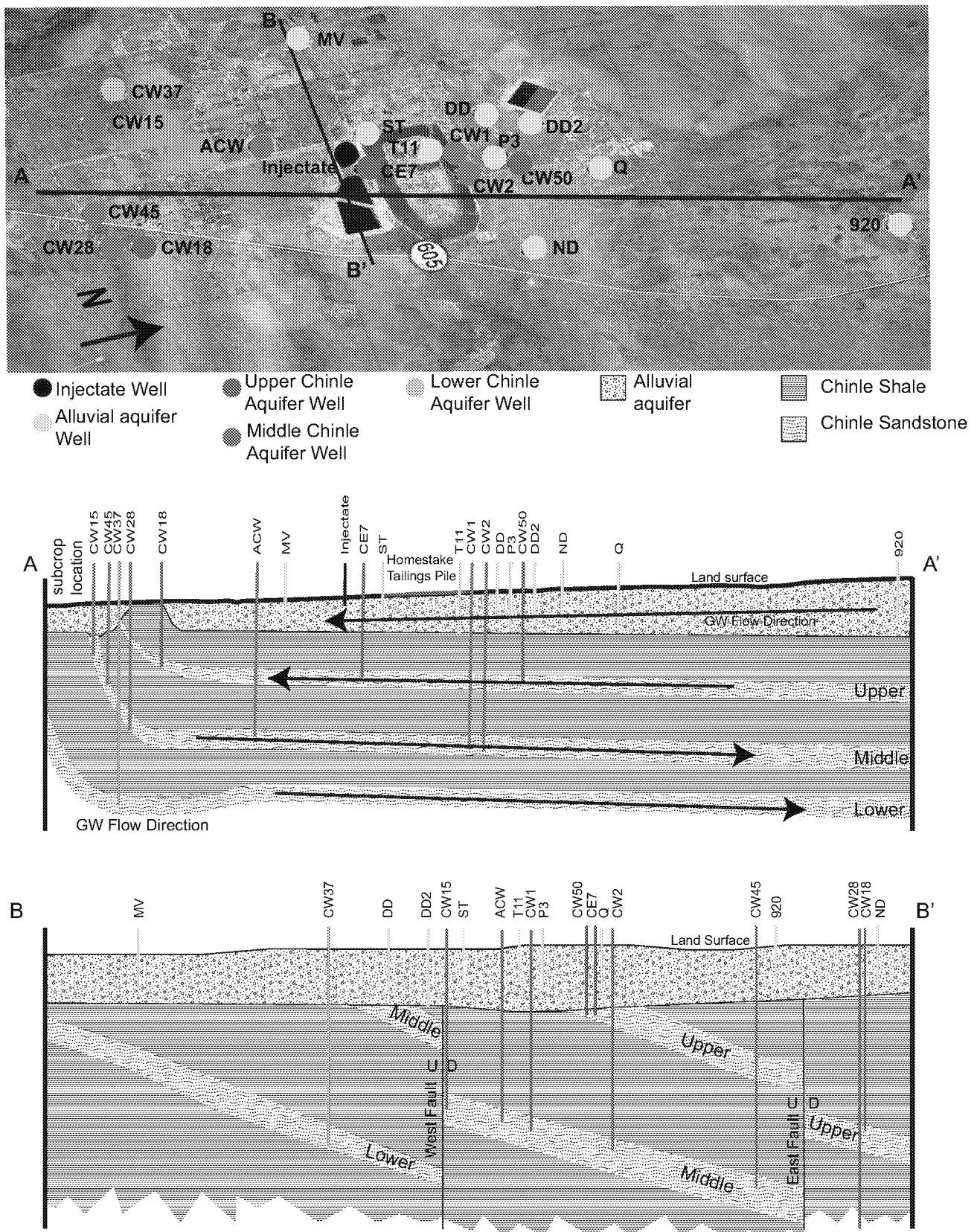
Company and Hydro-Engineering, LLC 2004). The areas of the Chinle Group aquifer in which the chemical composition of water has been altered by inflow of alluvial water are designated as the mixing zone, and have a cleanup standard of 160 µg/L U; parts of the formation in which the chemical composition of water has not been altered by inflow of alluvial water are designated as the non-mixing zone and have a different cleanup standard (Homestake Mining Company and Hydro-Engineering, LLC 2004).

The main objective of this paper is to differentiate the water type and source of U in groundwater in wells at and near the Site as either (1) sourced regionally from upgradient mining, (2) sourced locally by the mill Site, (3) sourced from deeper groundwater from the Chinle Group aquifer, and (4) sourced through other mechanisms such as upwelling from faults or mobility from surficial sediments. Water type and U source were determined using a geochemical fingerprinting approach of well-to-well variability and end-member variability. Multiple lines of evidence, including general chemistry, stable isotopes, radiogenic isotopes, borehole geophysics, groundwater age dating, and multivariate statistics were used to differentiate sources of water and specifically sources of U in the groundwater.

Geological setting and site description

The geology, hydrogeology, and hydrogeochemistry in the area are complex (Langman et al. 2012; Gallaher and Goad 1981). Numerous faults near the Site may affect the groundwater hydrogeology and geochemical interactions. In addition, the Chinle Group hydrogeologic units subcrop south of the Site (Fig. 2). Passive sampling of select wells in the area combined with spectral gamma-ray results indicate that alluvial aquifer stratigraphy and long screens in the monitoring wells play a role in degree of mixing in each well (Harte et al. 2019). The complexities of the site require rigorous analysis afforded by statistical techniques and multiple lines of evidence.

The Grants Mineral Belt is a southeast-trending zone of U deposits along the southern margin of the San Juan Basin in New Mexico (Brookins 1977). There are several mine and mill locations within the San Mateo Creek Basin, where the Site is located (Fig. 1a). The Site, north of Milan, New Mexico in the lower San Mateo Creek Basin, opened in 1958 and closed in 1990 (ATSDR 2009). The mill operations used an alkaline leach–caustic precipitation process to concentrate U from the ores (ATSDR 2009), using sodium carbonate and sodium bicarbonate (Nuclear Regulatory Commission 1981). Currently (2019), there are large and small tailings piles from mill processing and several evaporation ponds at the Site (Fig. 1b). As previously mentioned, these tailings sit atop an alluvial aquifer, which is underlain by the Upper, Middle, and Lower Chinle Group aquifers. Well names used



Conceptual models- not to scale

Fig. 2 Aerial image of the Site with well spatial locations, formation of completion, and cross-sectional locations. Cross sections A–A' and B–B' are shown below the aerial image. Arrows show the general direction of groundwater flow. The subcrops of the Chinle Group are shown in cross section A–A'. All figures are conceptual and based upon information presented in Hydro-Engineering LLC (2001) and Homestake Mining Company and Hydro-Engineering, LLC (2004)

in this study are those defined by the Site managers. Alluvial aquifer wells have the simplest alphabetic names and Chinle Group aquifer wells start with CW or CE (Fig. 1b).

The arroyo and ephemeral stream channels in the area are Quaternary (Holocene) alluvium with sand, gravel, and silt/clay in and adjacent to modern arroyo channels. The alluvium is generally 0–10 m thick and at or near the grade of modern channels (Cather 2011). Adjacent eolian and alluvial deposits from the Upper Pleistocene–Holocene, which are older than the arroyo and ephemeral stream deposits, have surface expression near the Site, likely because of uplift and erosion over geologic time. These older deposits of eolian sand and loessic silt are 0–10 m thick and have been locally reworked by alluvial processes (Cather 2011). The San Mateo Creek sediments are younger than the underlying eolian and alluvial deposits and may affect groundwater flow and geochemical processes based on the sediment sorting, grain size, mineralogy and chemical composition. For example, where sediments are coarse, groundwater flow is enhanced, and groundwater tends to be oxic (Turner-Peterson and Fishman 1986; Brookins 1977). In contrast, in finer grained sediment, groundwater flow rates are slow and water may be chemically reducing, which can affect mobility of redox-sensitive chemical elements such as U and Se (Turner-Peterson and Fishman 1986; Brookins 1977).

Sources of uranium at the site

Surface sediments collected in the 1970s through a program called the National Uranium Resource Evaluation (NURE) (U.S. Geological Survey, USGS 2004) show the distribution of U in soil samples and stream sediments in the San Mateo Creek Basin (Fig. 1c). Based on the NURE data, the ranges of soil and sediment U concentrations in four groupings are (1) the lowest concentration reported to the crustal average of 2.78 mg/kg (EPA 2008); (2) > 2.78 mg/kg to 5.00 mg/kg; (3) > 5.00 mg/kg to 20.0 mg/kg; and (4) > 20.0 mg/kg and 125 mg/kg. The highest concentrations of U in sediment are found near the San Mateo Creek, Ambrosia Lake, and Poison Canyon mines (Fig. 1a, c). Concentrations of U in sediments in Lobo Creek are generally lower than concentrations in San Mateo Creek and Arroyo del Puerto (Fig. 1a, c, d). These channels, Lobo Creek, San Mateo Creek, and Arroyo del Puerto, flow towards the Site and may affect the chemistry of sediments and water near the Site. The confluence of San Mateo Creek and Arroyo del Puerto, both ephemeral

creeks, lies in the upper San Mateo Creek Basin north of the Site (Langman et al. 2012). From the confluence, San Mateo Creek traverses southwest directly towards the Site (Fig. 1a, d). Over 30 years ago, the San Mateo Creek channel course was changed by Homestake Mining Company to flow to the west of the Site (Roca Honda Resources, LLC 2011); however, there is still a surface expression of the original channel in sediments from northeast to southwest to the north of the Site (Fig. 1d).

During active mining, mine discharge from Ambrosia Lake and San Mateo mines was directed into San Mateo Creek and Arroyo del Puerto; these ephemeral streams became perennial while mine discharge continued (Kaufman et al. 1976). There is evidence that groundwater in the area rose as much as 15 m (50 feet) from 1950 to 1980, then declined when mine discharge to the channels stopped (Weston Solutions, Inc. 2016). USGS streamgaging stations recorded discharge in the San Mateo Creek (1977–1982) and Arroyo del Puerto channels (1979–1982) above their confluence (USGS 2018) (Figure S1). Water from these channels may have infiltrated into shallow alluvial aquifers or evaporated, leaving behind constituents of concern such as U, Se, and radionuclides adsorbed or precipitated on alluvial sediments. Constituents in water that recharged the alluvial aquifer could be mobile under geochemical conditions appropriate for each constituent (NMED 2008). On the land surface, streambed sediments containing sorbed or precipitated constituents could be scoured and mobilized during larger storm events. Storm runoff could transport sediments containing mine water constituents downstream where they could be redeposited as stormflow recedes (Gallaher and Cary 1986). This process can readily occur during sporadic high-intensity rain events that occur during the summer monsoon season characteristic to this geographic area (Blake et al. 2017a).

Under current conditions, the San Mateo Creek and Arroyo del Puerto are ephemeral and further downstream, the Rio San Jose near Grants, NM, is perennial (Figure S1) (Roca Honda Resources, LLC 2011). The San Mateo Creek channel widens below the confluence with the Arroyo del Puerto, the slope of the channel decreases, and flow rarely reaches as far as a few miles past the confluence with Arroyo del Puerto (Roca Honda Resources, LLC 2011).

Water moves through the alluvium and Upper Chinle Group from northeast to southwest in the study area (Baldwin and Anderholm 1992). The general direction of flow in the Middle and Lower Chinle Group aquifers is from southwest to east and northeast and flow is down-dip (Langman et al. 2012) (Fig. 2). The dip of the Chinle Group aquifer is approximately to the north.

The Chinle Group is typically a confining unit in the area, with hydraulic conductivity values of the shale layers in the Chinle Group ranging from 10^{-1} to 10^{-8} ft/day (Baldwin

and Anderholm 1992; Baldwin and Rankin 1995). However, in between the shale layers are three layers of more coarse-grained deposits. In general, recharge to the Chinle Group aquifer is from downward leakage of water in the formation and can occur at subcrop locations (Fig. 2) (Baldwin and Anderholm 1992). There are two subsurface faults that cross the study area (Cather 2011) (Figs. 1b, d, 2). The Chinle Group aquifers are intersected by these faults that bound the overlying area of the large tailings pile. Along fault traces, permeability may be higher than in other areas (Fetter 2001), depending upon the material in the fault zone (Langman et al. 2012), resulting in a conduit for mixing between the alluvial and Chinle Group aquifers (ATSDR 2009). Groundwater mounding below the large tailings pile because of treated water injection has been reported (Home-stake Mining Company of California 2012); however, the present study did not focus on groundwater levels, but rather geochemical signatures of the groundwater.

Controls on uranium mobility

Uranium mobility is affected by redox, pH, and aqueous complexes. The insoluble form U(IV) is predominant in U ore (Brookins 1977; Hall et al. 2017) and can be oxidized in the presence of molecular oxygen or nitrate, among other constituents (Borch et al. 2010; Van Berk and Fu 2017). Once U(IV) solids are exposed to oxygen and oxidized during mining or milling, the oxidation state becomes U(VI) (Basu et al. 2015), which is mobile in water. In addition, abiotic and biotic nitrate reduction (denitrification) reactions may produce intermediates such as nitrite and nitrous oxide that will abiotically oxidize U(IV) to U(VI) (Nolan and Weber 2015; Senko et al. 2002). Microbial denitrification can be identified with stable isotopes of nitrogen and oxygen, where $\delta^{18}\text{O}$ -nitrate vs $\delta^{15}\text{N}$ -nitrate has a linear relation and high positive slope (Basu et al. 2015; Bottcher et al. 1990).

The dominant form of U adsorbed to sediments under oxidizing conditions is the uranyl ion, $(\text{UO}_2)^{2+}$ (Alam and Cheng 2014). In the presence of high carbonate concentrations in water and at pH of 6 and higher (Dong and Brooks 2006), uranyl ion–calcium–carbonate aqueous complexes are formed, which mobilizes U(VI) from sediments into water (Leavitt et al. 2011; Briganti et al. 2017). These reactions governing U mobility are potential transport and distribution pathways of U as a contaminant of concern.

Geochemical fingerprints

Geochemical constituents in groundwater that has recharged from the surface evolve due to interaction with rocks and sediments along the groundwater flow path. Geochemical

fingerprints expressed as major ion composition, U isotope ratios ($^{234}\text{U}/^{238}\text{U}$), radium isotopes (^{226}Ra and ^{228}Ra), radon concentrations (Rn), sulfur isotopes ($\delta^{34}\text{S}$), and stable isotopes of water [oxygen ($\delta^{18}\text{O}$) and hydrogen (δD)] can help to understand the type of water and source of U in groundwater (Basu et al. 2015; Yabusaki et al. 2007; Christensen et al. 2004; Zielinski et al. 1997).

The U activity ratio (UAR) of $^{234}\text{U}/^{238}\text{U}$ can indicate the origin of groundwater (Kamp and Morrison 2014). The ^{234}U isotope is a daughter of the ^{238}U isotope and when the UAR is equal to 1, the isotopes have reached secular equilibrium, and the activities are equal. U isotopes reach secular equilibrium in approximately 1 million years. Because the ore deposits in the area are older than 1 million years, the ore bodies are likely in secular equilibrium, and water with U derived from contact with mine tailings or mill sites should have a UAR equal to 1 (Corcho et al. 2015). The UAR of two discharge effluent samples collected in 1990 from the San Mateo Mine are reported as 1.06 and 1.07 (Van Metre et al. 1997). Additionally, the milling process completely dissolves the U ore minerals, which results in a theoretical UAR value of around 1–1.3 in the groundwater affected by the milling (Kamp and Morrison 2014). A UAR greater than 1 may indicate water unaffected by mine or mill tailings. For example, the UAR from samples in bedrock wells of the Dakota and Morrison Formations, thought to be unaffected by mining in the area, ranged from 2.0 to 6.7 (Van Metre et al. 1997).

Radium (Ra) isotopes and radon (Rn) concentrations in groundwater can indicate interaction with material from mines or mills. For instance, ^{226}Ra (a daughter product of radioactive decay of ^{238}U) concentrations tend to increase near ore bodies (Kaufman et al. 1976). Natural background concentrations of ^{226}Ra in the area are generally around 3 picocurie per liter (pCi/L), whereas the effluent from operating mines in the Grants Mineral Belt had ^{226}Ra concentrations of 100 pCi/L or more (Kaufman et al. 1976). Seepage from the large tailings pile had a ^{226}Ra concentration of 52 pCi/L (Kaufman et al. 1976). The range of Rn concentrations from groundwater percolating through U ore bodies can range from 2300 pCi/L to 109,000 pCi/L depending on the source of the water (Sahu et al. 2016). The Rn concentration in water can be diluted with increasing distance from the ore body (Sahu et al. 2016); however, because Rn has a half-life of 3.8 days, it does not persist far from its source and the dilution effect may be negligible.

Sulfate is a major constituent related to mine waste and mill tailings (Abdelouas 2006; Ries 1982). To differentiate between natural sulfate concentrations and concentrations related to mining or milling, stable sulfur isotopes of sulfate can be analyzed to identify the source of the sulfate (Kamp and Morrison 2014; Ries 1982). For example, $\delta^{34}\text{S}$ of sulfate values in groundwater surrounding the mill site located in

the Ambrosia Lake mining district range from -28.5 per mil (‰) to $+10.4$ ‰ (Ries 1982). Pyrite in sandstone-type U deposits in the Grants Mineral Belt has a $\delta^{34}\text{S}$ range of -27 ‰ to -1.8 ‰ (Jensen 1963). For the Faith Mine ore, located in Poison Canyon, $\delta^{34}\text{S}$ is equal to -27.2 ‰ and the $\delta^{34}\text{S}$ range identified from water in tailings ponds and groundwater near U mill sites in the Grants Mineral Belt and Navajo Nation is -5 ‰ to 5 ‰ (Kamp and Morrison 2014).

As relatively conservative isotopes, isotopic ratios of oxygen ($\delta^{18}\text{O}$) and hydrogen (δD) are not altered on contact with organic or geologic materials (Kendall and Caldwell 1998), which make them good chemical tracers of recharged water. However, the isotopes are affected by mass-dependent fractionation, which manifests as differences in physical and chemical properties based on the mass differences (Kendall and Caldwell 1998). These differences are related to temperature changes during precipitation and evaporation of water (Ingraham 1998) and occur during atmospheric exposure. Once precipitation enters the ground beyond the zone of evaporation, the isotopic signature is fixed. Stable isotopes δD and $\delta^{18}\text{O}$ can be indicative of recharge temperatures, evaporation, or upwelling from deep aquifers (Ingraham 1998; Robertson et al. 2016).

Conceptualization of U sources

Identifying the source of U at a site can be complex, especially in a location with multiple potential anthropogenic and natural sources. At this Site, there are four water sources defined: (1) regionally sourced from mining to the north of the Site; (2) locally sourced by the mill Site; (3) sourced from a deeper aquifer; and (4) other. Within each source, there is the potential for regional and local differences including contaminated and uncontaminated wells, natural heterogeneity, and differences in aquifers. The variability among the individual wells may be associated with the lithology, hydrogeology, or spatial location, which may be seen in Figs. 1 and 2. The specific geochemical signatures of each well were used to understand the general source water. Statistical analyses were used to narrow down the most appropriate geochemical signatures for this Site. Table 1 identifies the geochemical signature, description of the results that aid in identifying water source and relation to mining, and the associated figure in the text. In some cases, there may be more than one water source to a well.

Methods

Groundwater samples were collected from twenty wells both distal and proximal to the Site for an array of chemical constituents (Figs. 1b, 2; Blake et al. 2017b; Harte et al. 2018b) to help delineate chemical signatures associated with

the water sources in the area. A combination of monitoring wells, existing remedial extraction wells, and residential wells was sampled. Wells are screened in alluvium and in the Upper, Middle, and Lower Chinle Group aquifers. The injectate is water pumped from the tailings pile, treated in the reverse osmosis plant at the Site, and mixed with water from the San Andres-Glorieta Formation aquifer prior to injecting into the subsurface (Homestake Mining Company and Hydro-Engineering, LLC 2014) (injectate; Figs. 1b, 2). Groundwater-quality sampling followed volumetric purging procedures as outlined in the USGS National Field Manual (USGS 2006). Details of sampling, collection, preservation techniques, and chemical analyses are included in the Supplementary Information (SI).

Three multivariate statistical techniques, principal component analysis (PCA), non-metric multidimensional scaling (NMDS), and cluster analysis were used to quantitatively investigate the similarities and differences in groundwater geochemistry in the wells (de Carvalho Filho et al. 2017; Jiang et al. 2015). Details of these techniques are included in the SI.

For this study, the following constituents were used as input for the PCA, NMDS, and cluster analysis: gross alpha, gross beta, ^{226}Ra , ^{228}Ra , ^{234}U , ^{238}U , uranium concentrations, alkalinity, calcium, iron, magnesium, chloride, sulfate, sodium, molybdenum, and vanadium. These constituents were chosen based on the component loadings calculated from PCA when using all measured constituents. The constituents chosen had at least a 0.8 component loading when compared with all measured constituents.

Piper diagrams were created using GWChart (USGS 2015). Geochemical modeling to determine aqueous complexes and mineral saturation indices was completed in PHREEQC version 3.4.0.12927 using the minteqv4 database (Parkhurst and Appelo 1999). Major and trace element chemistry data of filtered water from each well were used as input for the model and are accessible in the corresponding data release (Blake et al. 2017b). Groundwater ages based on dating of well samples were used to calculate groundwater travel times at the Site. Details are given in the SI.

Results and discussion

Each section of the results and discussion describes the line of evidence used to identify the source of U to each well. Groups of wells with similar signatures are discussed.

Major water types

Two dominant end members in waters from the wells sampled in this study, sulfate–calcium ($\text{SO}_4\text{--Ca}$) and sulfate–sodium plus potassium ($\text{SO}_4\text{--Na + K}$), are identified in

Table 1 Geochemical signature and water source descriptions

Water source	Piper diagram (Fig. 3)	Co-constituents (Fig. 4 and S2)	PCA (Fig. 6a,b)	NMDS (Fig. 6c)	Cluster (Fig. 6d)	$^{234}\text{U}/^{238}\text{U}$ (Fig. 7a)	Radon (Fig. 7b)	Radium (Fig. 7c)	Gross alpha/beta (Fig. 7d)
1. Regionally sourced from upgradient mining	Wells that near each other have similar water types. End members and wells mixed between end members can be identified	Higher U concentration, likely closer to source. High TDS may indicate mining or mill source	Wells that plot near each other may have the same or similar water sources	Wells that plot near each other may have the same or similar water sources	Wells that plot near each other may have the same or similar water sources	UAR = 1, mining or mill tailings signature. UAR > 1.3 may not be affected by mining or mill tailings. UAR between 1 and 1.3 may show mixing	High radon may be associated with inputs from faults or proximity to uranium source	High Ra concentrations may indicate proximity to source	High Gross Alpha may show wells with radioactive sediments
1a. San Mateo Creek Channel (Fig. 1d): wells within the channel may be affected by mine discharge and adsorption or precipitation on sediments	Wells that near each other have similar water types. End members and wells mixed between end member can be identified	Higher U concentration, likely closer to source. High TDS may indicate mining or mill source	Wells that plot near each other may have the same or similar water sources	Wells that plot near each other may have the same or similar water sources	Wells that plot near each other may have the same or similar water sources	UAR = 1, mining or mill tailings signature. UAR > 1.3 may not be affected by mining or mill tailings. UAR between 1 and 1.3 may show mixing	High radon may be associated with inputs from faults or proximity to uranium source	High Ra concentrations may indicate proximity to source	High Gross Alpha may show wells with radioactive sediments
2. Locally sourced by the mill Site	Wells that near each other have similar water types. End members and wells mixed between end members can be identified	The subcrop area may allow for mixing from the Site to the Chinle Group aquifer	Wells that plot near each other may have the same or similar water sources	Wells that plot near each other may have the same or similar water sources	Wells that plot near each other may have the same or similar water sources	UAR = 1, mining or mill tailings signature. UAR > 1.3 may not be affected by mining or mill tailings. UAR between 1 and 1.3 may show mixing	High radon may be associated with inputs from faults or proximity to uranium source	High Ra concentrations may indicate proximity to source	High Gross Alpha may show wells with radioactive sediments
3. Sourced from deeper aquifer groundwater	Wells that plot near each other have similar water types. End members and wells mixed between end members can be identified	The subcrop area may allow for mixing from the Site to the Chinle Group aquifer	Wells that plot near each other may have the same or similar water sources	Wells that plot near each other may have the same or similar water sources	Wells that plot near each other may have the same or similar water sources		High radon may be associated with inputs from faults or proximity to uranium source		Not a clear indicator of U source

Table 1 (continued)

Water source	Piper diagram (Fig. 3)	Co-constituents (Fig. 4 and S2)	PCA (Fig. 6a,b)	NMDS (Fig. 6c)	Cluster (Fig. 6d)	$^{234}\text{U}/^{238}\text{U}$ (Fig. 7a)	Radon (Fig. 7b)	Radium (Fig. 7c)	Gross alpha/beta (Fig. 7d)
3a. Near fault (Fig. 1b): wells close to the faults may have upwelling of water from deeper ground-water	Wells that plot near each other have similar water types. End members and wells mixed between end members can be identified	The subcrop area may allow for mixing from the Site to the Chinle Group aquifer	Wells that plot near each other may have the same or similar water sources	Wells that plot near each other may have the same or similar water sources	Wells that plot near each other may have the same or similar water sources		High radon may be associated with inputs from faults or proximity to uranium source		Not a clear indicator of U source
3b. Near Subcrop (Fig. 2): potential for mixing between alluvial and Chinle aquifers	Wells that plot near each other have similar water types. End members and wells mixed between end members can be identified	The subcrop area may allow for mixing from the Site to the Chinle Group aquifer	Wells that plot near each other may have the same or similar water sources	Wells that plot near each other may have the same or similar water sources	Wells that plot near each other may have the same or similar water sources		High radon may be associated with inputs from faults or proximity to uranium source		Not a clear indicator of U source
4. Other sources	Well fits more than one category or final category is unclear	Well fits more than one category or final category is unclear	Well fits more than one category or final category is unclear	Well fits more than one category or final category is unclear	Well fits more than one category or final category is unclear	UAR = 1, mining or mill tailings signature. UAR > 1.3 may not be affected by mining or mill tailings. UAR between 1 and 1.3 may show mixing	Well fits more than one category or final category is unclear	Well fits more than one category or final category is unclear	not a clear indicator of U source

Each geochemical signature was used to interpret the source of water to individual wells

PCA principal components analysis, NMDS non-metric multidimensional scaling

the Piper diagram (Fig. 3). End member 1, $\text{SO}_4\text{--Ca}$, is similar to mine water discharge from the Arroyo Puerto Mine in the Ambrosia Lake mining district (Gallaher and Cary 1986). The alluvial aquifer wells DD, DD2, P3, 920, and Q plot in this area. These wells are within the San Mateo Creek channel and may indicate an influence from a water source to the north.

End member 2, $\text{SO}_4\text{--Na} + \text{K}$, is more dominant in groundwater from the Middle Chinle Group aquifer than from the alluvium at the Site. However, groundwater from the large tailings pile (well T11) also plots in end member 2. This may confirm that well T11 is drilled into the Chinle Group aquifer. Mine waters in the Grants Mineral Belt can contain higher concentrations of sodium and sulfate compared to natural waters (NMED 2008), which

may account for the higher values of these constituents in well T11. $\text{Na--SO}_4\text{--Cl}$ groundwater is commonly created by dissolution of evaporite minerals such as gypsum (CaSO_4) and halite (NaCl) (Vengosh 2003); evaporite dissolution could influence the composition of end member 2 groundwater samples. The Chinle Group is known to have gypsum deposits in some locations (Cather 2011), and the aridity of the region may cause evaporite or salt deposits in the alluvium. Evaporite crystals have been observed in sediments along the Rio San Jose, which flows through the Grants Mineral Belt (Popp et al. 1983). Wells that plot between the two end members in Fig. 3 vary in aquifer type and spatial location, which further demonstrates the complexity of groundwater source and composition in wells at this site.

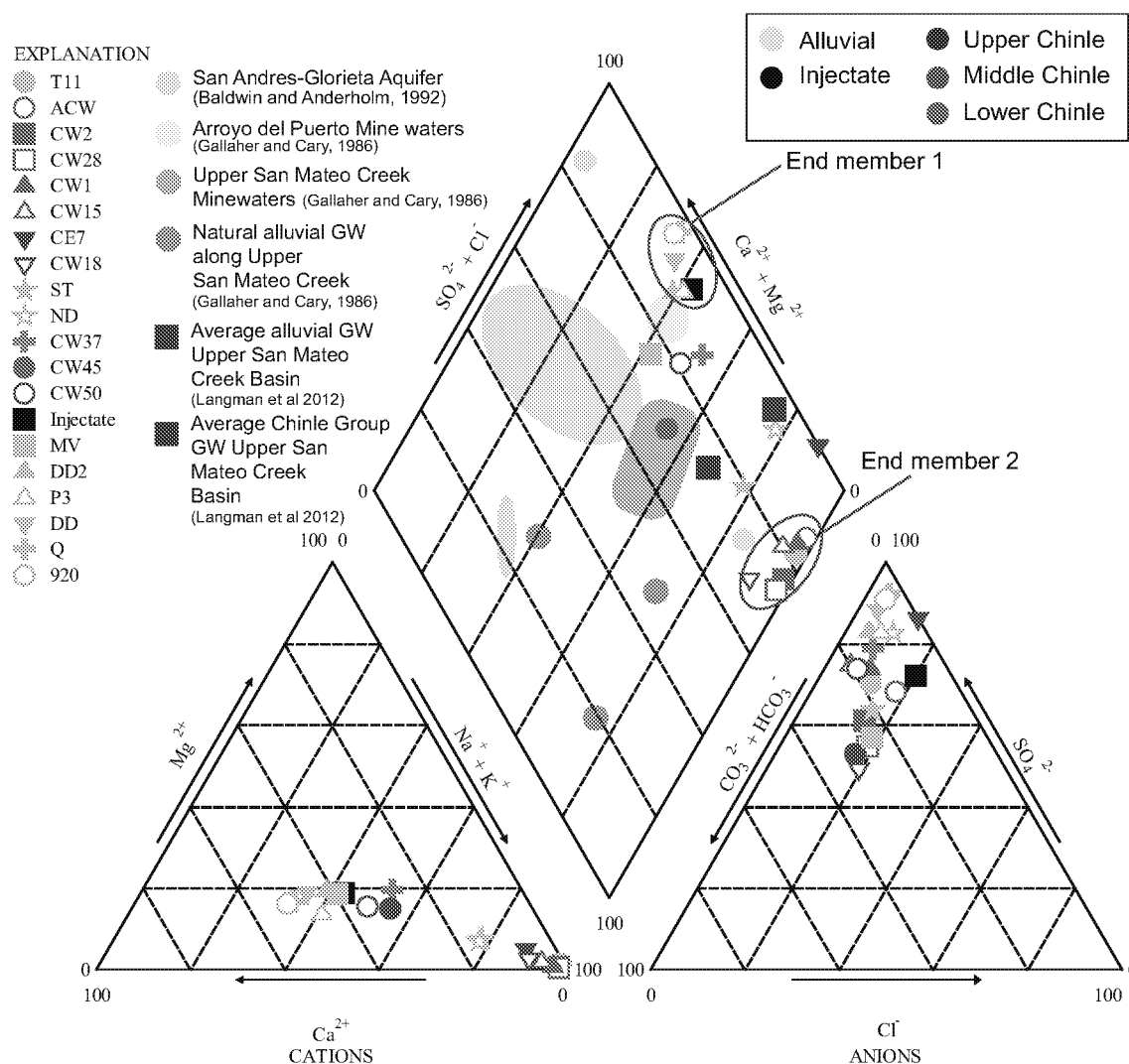


Fig. 3 Piper diagram of groundwater chemistry from wells sampled for this study. Regional groundwater data are included for comparison

Uranium, selenium, and molybdenum concentrations in groundwater

Uranium concentrations in water samples from the Site fall into three broad categories: (1) less than the drinking water standard of 30 $\mu\text{g/L}$ ($n=3$), (2) from 30 to 100 $\mu\text{g/L}$ ($n=9$), and (3) greater than 100 $\mu\text{g/L}$ ($n=8$). Uranium concentrations in groundwater collected from the Site range from 25.0 to 22,700 $\mu\text{g/L}$ (Fig. 4a, b) as reported in Harte et al. (2018a). The three highest dissolved U concentrations were measured in wells within and directly south of the large tailings pile [Chinle Group aquifer: CE7 (22,700 $\mu\text{g/L}$), Alluvial aquifer: T11 (10,029 $\mu\text{g/L}$), and ST (2709 $\mu\text{g/L}$)] and the three lowest U concentrations were measured in ND (25.0 $\mu\text{g/L}$), P3 (26.0 $\mu\text{g/L}$), and CW18 (28.0 $\mu\text{g/L}$), which are not spatially adjacent to each other. The higher U concentrations in CE7, T11, and ST were expected based on historical data and proximity to the U milling operations. Alluvial wells 920, DD2, DD, T11, MV, ST, and Chinle Group wells CE7 and CW45 have U concentrations greater than 100 $\mu\text{g/L}$, which could indicate a source from mining or milling. Given the proximity of alluvial wells 920, DD2, DD, and MV to the San Mateo Creek channel (Fig. 1a, b), these U concentrations may indicate an effect from mine dewatering. The dewatered mine water recharged the alluvium north of the Site from the upper San Mateo basin. Sediments transported in the San Mateo Creek channel from north to south contained potentially higher U source concentrations. If the dewatered mine water encountered subsurface reducing conditions, U would precipitate out of solution, and could serve as a source of U if exposed to oxic conditions. Wells T11, ST, and CE7 are adjacent to the tailings pile and water in these wells may be affected by activities at the Site. Water from well CW45 may reflect mixing with the alluvial aquifer due to its proximity to the subcrop area (Fig. 2).

Well DD ($U=103 \mu\text{g/L}$), which is spatially adjacent to well DD2, has a U concentration less than half of the concentration of DD2 ($U=250 \mu\text{g/L}$). The western fault at the Site is closer to DD2 than to DD (Figs. 1b, 2), and upwelled water from the fault may contribute to water in DD2. Well DD2 is drilled approximately 3 m (10 ft) into the upper Chinle Group Shale and is partially screened in the Chinle Group Shale. Wells DD and DD2 are adjacent to the western evaporation ponds, which may have an effect on the U concentrations in these wells, although leakage was not considered because the evaporation pond was reported to be lined (Homestake Mining Company and Hydro-Engineering, LLC 2014). Further evaluation of leakage from the evaporation pond may be beneficial.

The concentration of Se and Mo vary among the wells. The EPA drinking water standard for selenium is 50 $\mu\text{g/L}$ and the highest concentration of Se was in well CE7 (900 $\mu\text{g/L}$; Fig. 4a, c). Wells Q, P3, and 920 (Fig. 4a, c)

also had elevated Se concentrations (470, 300, and 290 $\mu\text{g/L}$, respectively). Selenium concentrations in sediments related to the Poison Canyon area are generally high (Gallaher and Cary 1986), and these sediments could be the source of elevated Se in the wells upgradient from the Site. The average Se concentration in discharge to the San Mateo Creek drainage from the Ambrosia Lake Mining District was 240 $\mu\text{g/L}$ (Gallaher and Cary 1986). Well DD has a Se concentration 33 times higher than that found in well DD2. This result may be explained by proximity to Poison Canyon, mixing from the middle Chinle Group aquifer waters, and/or mixing with groundwater from the nearby fault.

Wells CE7, T11 and ST have the highest concentrations of Mo, at 28,000, 22,000, and 3500 $\mu\text{g/L}$, respectively, which follows the same pattern as the elevated U concentrations (Fig. 4b, c) and may be explained by the fact that U and Mo are often the most mobile elements associated with U mills (Morrison and Spangler 1992). Well CW18 may have a different source of the elevated Mo due to the higher concentration compared to nearby wells.

In addition to U or Mo concentrations, total dissolved solids (TDS) may be indicative of U source water or mixed water. For instance, the average TDS concentration in alluvial groundwater upgradient of the San Mateo Creek mine was 400 mg/L (Brod and Stone 1981) and the average TDS in alluvial groundwater north of Arroyo del Puerto, in the Ambrosia Lake mining area, was 5900 mg/L (Brod and Stone 1981). Additionally, the average TDS concentration in alluvial groundwater below the confluence of Arroyo del Puerto and San Mateo Creek was 2000 mg/L (Kaufman et al. 1976) (Figure S2). The TDS concentrations from the alluvial wells sampled for this study range from 2000 mg/L (ND) to 7500 mg/L (T11). Wells MV, P3, 920, DD2, and Q have concentrations between 2000 and 3000 mg/L and wells DD and ST both have TDS concentrations of 3700 mg/L (Figure S2). These results suggest that wells north of the Site may have mine discharge water associated with them. The similarity of TDS in groundwater from well DD and ST may suggest that well DD has water from the upgradient evaporation pond seeping into the groundwater or water from the large tailings pile being transported in groundwater to the well.

Uranium mobility

Geochemical modeling

Geochemical modeling results show that the dominant species of U in the groundwater of the sampled wells is $U(VI)$, which is typical of the species related to surface mining and milling activities. The dominant aqueous complex is a uranyl carbonate, which suggests that U in groundwater is mobile. However, the presence of hydrous ferric oxides (HFO) in sediments can increase the sorption of U to

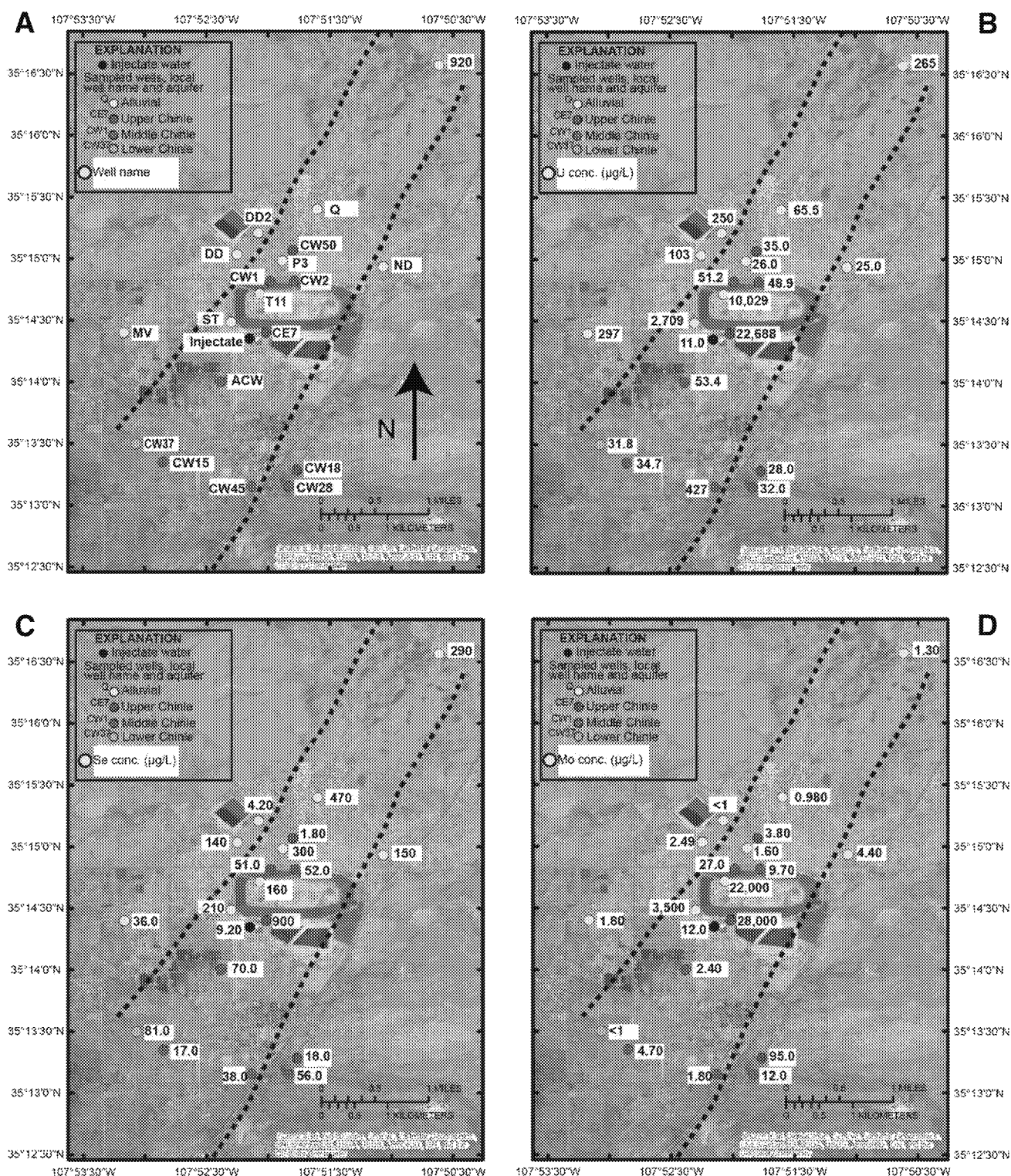


Fig. 4 Aerial photos of Site with **a** well names, **b** uranium concentrations, **c** selenium concentrations, and **d** molybdenum concentrations measured in each well at the time of sampling

sediments (Johnson et al. 2016). Harte et al. (2019) reports U spectral gamma spikes in some red clays at the Site, which are likely associated with HFOs. Water in all the samples

were supersaturated with respect to the HFOs ferrihydrite ($(\text{Fe}^{3+})_2\text{O}_3 \cdot 0.5\text{H}_2\text{O}$), goethite ($\text{FeO}(\text{OH})$), and lepidocrocite ($\gamma\text{-FeO}(\text{OH})$).

Nitrogen isotopes and redox

The comparison of $\delta^{18}\text{O}$ -nitrate vs. $\delta^{15}\text{N}$ -nitrate for the alluvial groundwater and Chinle Group groundwater shows that the alluvial groundwater has the signature of isotope fractionation related to denitrification, a relation of 1:~2 (Bottcher et al. 1990) (Fig. 5). The alluvial groundwater relation is 1:2.3 (Fig. 5) and the Chinle Group wells do not have the 1:2.3 relation suggesting that denitrification does not affect the Chinle Group wells. Denitrification reactions can produce intermediates such as nitrite and nitrous oxide that will abiotically oxidize U(IV) to U(VI), which could be the case in the alluvial aquifer (Nolan and Weber 2015; Senko et al. 2002). In addition, based on data presented in Bottcher et al. (1990), the alluvial and Chinle Group wells with lower $\delta^{18}\text{O}$ -nitrate and $\delta^{15}\text{N}$ -nitrate values (P3, ND, and CW37) may be affected by nitrogen fertilizers.

Multivariate statistics

PCA, NMDS, and cluster analysis were used to identify important geochemical fingerprints for further evaluation. Principal component 1 (PC1) accounts for 65.45% of the variance in this dataset and principal component 2 (PC2) accounts for 19.56% of the variance (Fig. 6a, b). Constituents with the highest loadings for PC1, which suggests that these constituents account for the major differences among the geochemistry of the wells, based on the PCA include SO_4^{2-} , Gross beta, ^{228}Ra , U, ^{238}U , ^{234}U , ^{235}U , gross alpha, Mo, Cl, and Na (Fig. 6a). Constituents with the highest loadings for PC2 include Fe, Ca, and Mg, which suggests that these constituents have a secondary effect on the variance in geochemistry among the wells. The distribution of the wells in the plot describes the variability in each well and

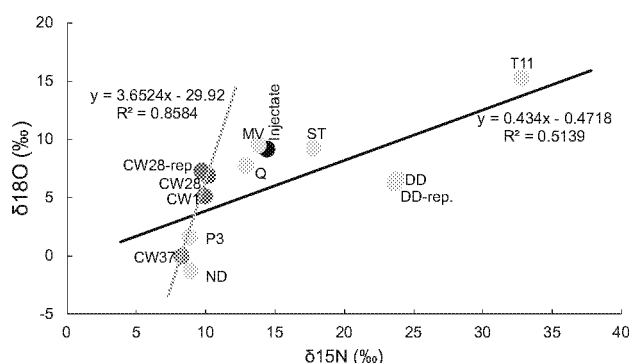


Fig. 5 Plot of $\delta^{18}\text{O}$ -nitrate vs. $\delta^{15}\text{N}$ -nitrate. Trendlines are plotted for alluvial aquifer wells (including injectate) and Chinle Group aquifer wells. The alluvial wells have a 1:2.3 relation between $\delta^{18}\text{O}$ -nitrate and $\delta^{15}\text{N}$ -nitrate. The Chinle Group aquifer wells do not show the 1:2.3 relation. Yellow circles are alluvial wells, green circles are Middle Chinle Group aquifer wells, orange circles are Upper Chinle Group aquifer wells, and the black circle is the injectate

how each well is associated with other wells (Fig. 6b). For instance, DD, Q, 920, and DD2 plot near each other while CE7 and T11 plot far from all other wells and outside of the 95% prediction ellipse.

The NMDS plot shows a slightly different distribution of the wells compared to the PCA results (Fig. 6c). The clearest differences are the separation of Q from the cluster with 920, DD, and DD2, and the closer distribution of CE7, ST, and T11. The NMDS solution converged after 20 iterations and the stress value was 0.0959442, which is indicative of a robust solution (Buttigieg and Ramette 2014). The cluster analysis shows similar well clusters to the NMDS analysis (Fig. 6d).

When comparing the results from PCA, NMDS, and cluster analysis, the following groups of wells consistently plot together: (1) 920, DD, and DD2; (2) CW15, CW18, ACW, CW28, CW1, CW2; and (3) injectate and ND. The following wells plot near each other in two of the three analyses: (1) CE7, ST, T11; (2) CW45, MV; (3) CW37, P3; and (4) CW50, injectate. Well Q is the only well that does not consistently plot near the other wells, which shows the chemistry is different from nearby wells.

The grouping or clustering is based on statistical comparisons, and certain trends are discernible. The most notable trend is that the local operations at the Site are identifiable at three wells (T11, ST, and CE7) proximal to the site, which relates to U mobility and large U concentrations at these sites (Fig. 4b), and no other wells are associated with this cluster. In contrast, the remaining wells are less distinct from each other and clustered into three groups. Wells proximal to the large tailings pile such as DD and DD2 tend to be associated with regional or local Site impacts.

Radiogenic fingerprints

Uranium isotope ratios

The alluvial well (T11) within the large tailings pile, and the alluvial (ST) and upper Chinle Group well (CE7) directly south of the large tailings pile at the Site, have $^{234}\text{U}/^{238}\text{U}$ activity ratios (UAR) of nearly 1 (Fig. 7a). This indicates that the groundwater in these wells has the signature of the mill tailings pile. Groundwater in wells CW45, CW50, MV, Q, P3, and 920 as well as the injectate water have UAR values between 1 and 1.3 (Fig. 7a). There is evidence that UAR values greater than 1.3 are likely unaffected by mining or mill tailings (Zielinski et al. 1997). However, there is also evidence that UAR values may be higher in groundwater in this area because of prolonged interaction with U-rich sediments (Johnson and Wirt 2009; Zielinski et al. 1997). Therefore, based on the UAR values, the wells that have UAR values between 1 and 1.3 may be affected by mining or mill tailings, may have a mix of unaffected and affected

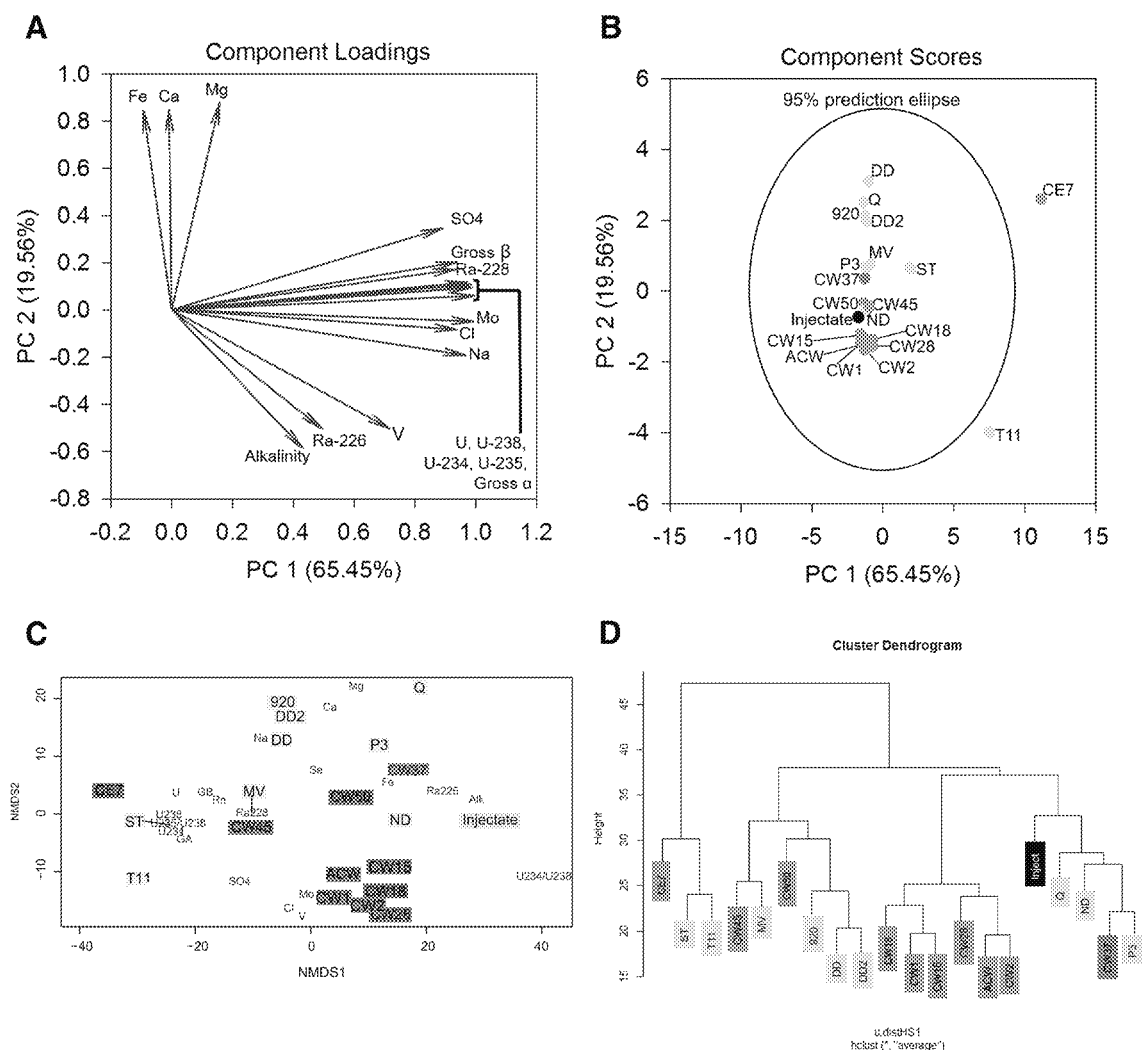


Fig. 6 Plots of multivariate statistical analyses: **a**, **b** PCA, **c** NMDS, and **d** cluster analysis

water, or may be in contact with U-rich sediments for longer periods of time.

Radon

The highest ^{222}Rn activity was found in wells DD2, CE7, T11, and CW50 (Fig. 7b). Wells CE7 and CW50 are screened in the same aquifer, the Upper Chinle Group, where the flow direction is generally from north to south under the tailings pile. Well DD2 is located adjacent to a sub-surface fault (Fig. 1b), where there is potential for ^{222}Rn to seep to the surface. Additionally, well DD2 is near the western evaporation ponds, which could be the source of the radon. T11 is in direct contact with mine tailings, which may explain the elevated ^{222}Rn activity. Radon has a short half-life (3.8 days); therefore, the water sampled from these wells must be near its source for the radon to present in high concentrations. Alternately, the high radon concentrations

may be attributed to the high concentrations of parent material (^{226}Ra) in the water.

^{226}Ra and ^{228}Ra

The distribution of ^{226}Ra and ^{228}Ra among the wells shows T11 having the highest concentration of ^{226}Ra (3.82 pCi/L) and CE7 having the highest concentration of ^{228}Ra (5.88 pCi/L) (Fig. 7c). Gallaher and Goad (1981) reported that the San Mateo area discharge from treated mine waters had ^{226}Ra concentrations of 23 ± 1 ($n=3$) pCi/L and the Ambrosia Lake discharge waters had ^{226}Ra concentrations of 4.6 ± 0.2 ($n=3$). Both reported ^{226}Ra concentrations are higher than those found in the wells sampled in this study, except for T11. Previous studies in Grants Mineral Belt streams show that ^{226}Ra generally forms insoluble precipitates or adsorbs to sediments within ten river miles of the

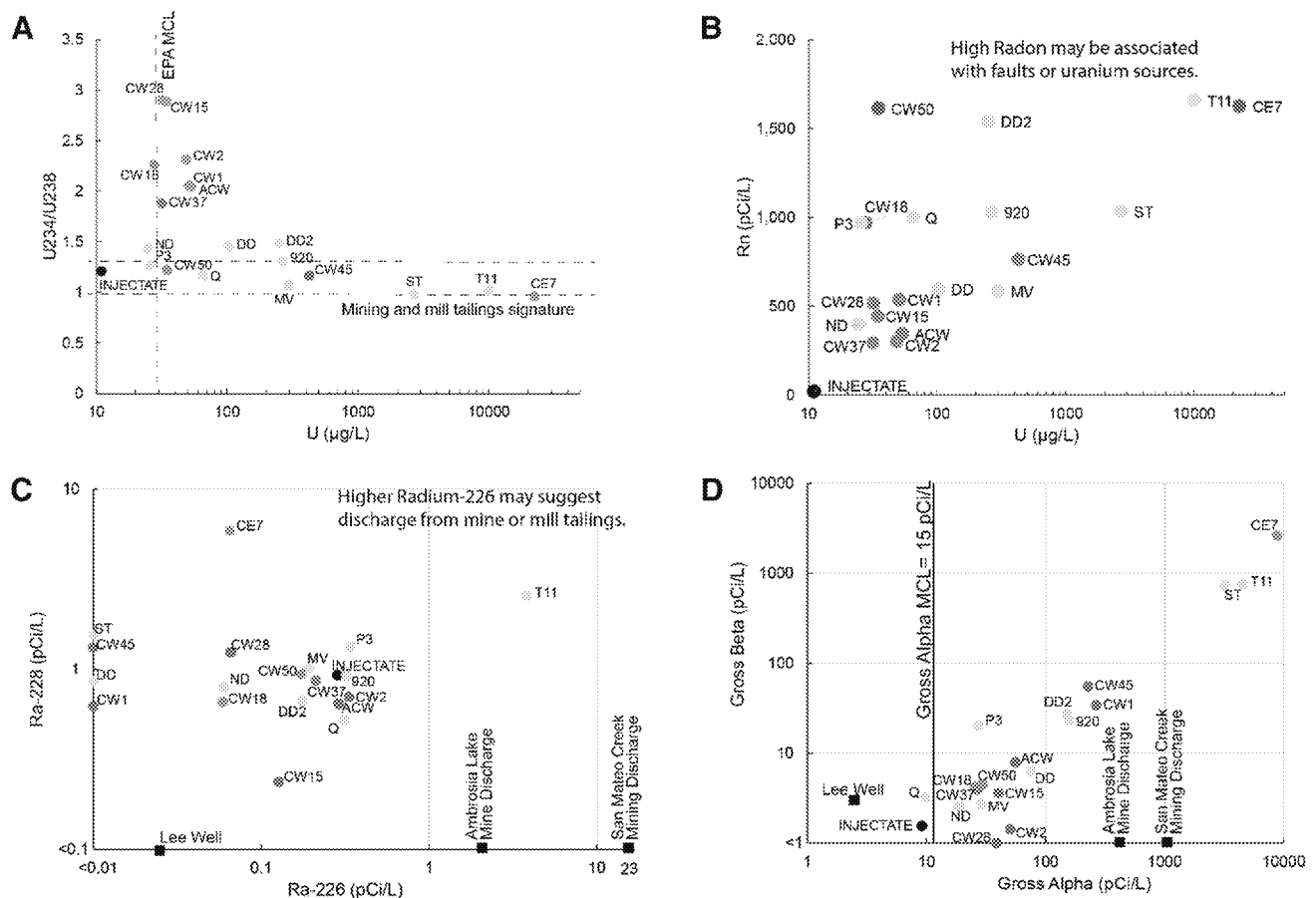


Fig. 7 Plots of **a** $^{234}\text{U}/^{238}\text{U}$ activity ratio vs. U concentration, **b** Rn concentration vs. U concentration, **c** ^{226}Ra vs. ^{228}Ra (pCi/L), and **d** gross alpha vs. gross beta

source (Gallaher and Cary 1986) and, therefore, ^{226}Ra is not found in high concentrations in groundwater in the area.

Gross alpha–beta

The gross alpha–beta results from the groundwater wells sampled reveal a distribution across the wells (Fig. 7d); eighteen of twenty wells have gross alpha values greater than the 15 pCi/L EPA MCL (EPA 2017), and CE7, ST, and T11 have the highest gross alpha–beta results. The injectate has the lowest gross alpha–beta results (Fig. 7d). Gallaher and Goad (1981) reported that treated mine effluents that discharged to San Mateo Creek and Arroyo del Puerto had gross alpha values of 1100 pCi/L ($n=3$) from the San Mateo Area and 580 ± 70 pCi/L ($n=5$) from the Ambrosia Lake area (Fig. 7d). These values are higher than the gross alpha values reported for the majority of the wells, with the exception of DD2, 920, CW1, CW45, ST, T11, and CE7. These wells with high gross alpha concentrations may have sediments with radioactive materials in contact with the water.

Stable isotopes

The stable isotopes of water (Figure S3) and sulfur (Figure S4) identify general trends of the wells. For instance, the majority of the Chinle Group wells have more negative δD and $\delta^{18}\text{O}$ values while the alluvial wells are less negative. The three wells most proximal to the large tailings have high sulfate and less negative $\delta^{34}\text{S}$ values. The alluvial wells most north of the large tailings pile have intermediate sulfate concentrations and more negative $\delta^{34}\text{S}$ values. Discussion of these trends is included in the SI.

Groundwater travel time

Groundwater travel time between wells Q and MV could be as fast as 0.30 m/day [1 ft/day (365 ft/year)] (Figure S5) as determined by the presence of environmental tracers tritium/helium and CFCs. This suggests that groundwater could travel nearly 10,000 ft (the distance between Q and MV) in 27 years. If mine water discharge in streams recharged the alluvial aquifer a few miles below the confluence of the San

Mateo Creek and Arroyo del Puerto, groundwater from this process would travel to the Site in approximately 60 years.

Source water comparisons in wells

Surface and subsurface structures near the Site reveal a complex interaction of water from mine discharge, Chinle Group and alluvial aquifer mixing and upwelling from faults, effects from the large tailings pile at the Site, and other unidentified sources. Our procedure to interpret the geochemical fingerprinting of groundwater, based on multiple lines of evidence, is shown in Table 1. Our conclusions on sources of water and U in the water are shown in Table 2.

Results suggest that alluvial wells north of the Site have fingerprints from regional sources related to upgradient mining. Alluvial wells on the western side of the Site have regionally upgradient mining water sources, signatures of the mill Site, deeper groundwater or water upwelled from faults, and potentially other sources such as the nearby evaporation ponds. The two alluvial wells closest to the large tailings pile (T11 and ST) and one Upper Chinle Group aquifer well (CE7) directly south of the large tailings pile have the most consistent fingerprints of the local mill tailings. All the deeper Chinle Group wells except two (CW1 and CW2) are mixed with alluvial water that may be affected by the Site water and deeper alluvial groundwater. Deeper groundwater and another unidentified source are the likely source of water in the alluvial well on the eastern side of the Site (ND).

The alluvial wells north of the site, 920, Q, and P3, all appear to have water sourced from regionally upgradient mining based on U concentrations, similar UAR values, and locations within the San Mateo Creek Channel, which may have legacy mining signatures associated with the sediments. Travel time calculated between Wells Q and MV based on age dating suggests that alluvial water may have had time to move the 3000 m (10,000 ft) between the wells (Figure S5; Table S2). Groundwater in wells DD, DD2, and MV not only appears to have regional mining water sources, but also show signatures of the mill Site (DD2 and MV), deeper groundwater or water upwelled from faults (DD2), and potentially

other sources (DD2 and DD) such as the nearby evaporation ponds (Fig. 1b). Water in well DD2 may be influenced by the deposition of sediments or infiltration of stream water from the San Mateo Creek channel, but also influenced by the western fault. Wells T11 and ST show the most evidence of water sourced from the mill Site on the basis of U and Mo concentrations, UAR values, and Rn concentrations. Well CE7 also shows evidence of water sourced from the mill Site, but is completed in the Upper Chinle Group aquifer, so it likely has a mixed source of water. Wells ST, T11, and CE7 are directly within or adjacent to the large tailings pile and, therefore, the gross alpha signature may be related to contact with the mill tailings.

Well ND has some geochemical similarities to alluvial wells P3, Q, and the injectate, but may be mixed with deeper aquifer water based on the Piper diagram and passive sampling results reported in Harte et al. (2019). In addition, well ND is located east of the eastern fault and within the Lobo Canyon deposits; therefore, well ND may have another source of water that is unidentified. The injectate water is known to be a mixture of reverse osmosis water and the San Andres-Glorieta Formation aquifer water.

Well CW45 is in the subcrop area at the southern edge of the Site and may be affected by alluvial waters or from upwelling from the eastern fault. Based on knowledge of the subcropped geology in the southern and western portions of the Site, it is suggested that wells CW18, CW15, CW45, ACW and CW28 are within the mixing zone between the alluvial aquifer and the Chinle Group aquifer. In addition, the wells located in the mixing zone and between the two faults, and south of the large tailings pile (ACW, CW15 and CW45) are considered affected by tailings seepage (Hydro-Engineering 2001). All of the Middle Chinle Group wells plot in the End Member 2 area of the Piper Diagram except for sampled well water from CW45, which plots in the mixed area. In addition, CW45 plots closer to MV in the NMDS biplot and the cluster analysis, which may provide further evidence of mixed water.

Well CW50 is north of the large tailings pile and in the upper Chinle Group aquifer. This well may be a mixture of

Table 2 Wells sampled in this study with their likely source(s) of water

Water source	920	Q	ND	DD2	DD	P3	T11	ST	MV	CW49	CE7	CW18	CW1	CW2	ACW	CW15	CW45	CW28	CW37	INJECTATE
1. Regionally sourced from upgradient mining	X	X		X	X	X			X											
1a. San Mateo Creek Channel	X	X		X		X														
2. Locally sourced by the mill Site				X			X	X	X	X	X	X			X	X	X	X	X	
3. Sourced from deeper aquifer groundwater			X	X						X	X	X	X	X	X	X	X	X	X	
3a. Near fault			X	X													X			
3b. Near Subcrop												X			X	X	X	X		
4. Other source			X	X	X															X

The alluvial aquifer wells are highlighted in yellow, Upper Chinle Group aquifer in blue, Middle Chinle Group aquifer in green, and Lower Chinle Group aquifer in orange. The injectate water is shown in black. Samples within each aquifer are listed from north to south

alluvial and Chinle Group water, as supported by the Piper Diagram, multivariate analysis, and UAR. Additionally, well CW50 had the highest Rn concentration of all wells, which may indicate radioactive sediments. This well is not close to either fault. Well CW37 is the only lower Chinle Group well sampled and may have a mixture of alluvial and Chinle Group water, as shown in the Piper diagram and multivariate analysis. Wells CW1 and CW2 are slightly north of the large tailings pile and are in the Middle Chinle Group aquifer. Both wells plot in End Member 2 on the Piper Diagram but have UAR values above 1.3 and low Rn concentrations, which may indicate that the water is predominantly from the Chinle Group aquifer. The Chinle Group waters with an X in the 'locally sourced by the mill Site' category in Table 2 may contain waters affected by the Site, but further study is required to identify this source.

Conclusions

The Homestake uranium mill site is a very complex hydrogeological system because of the geology, naturally occurring elements, and various anthropogenic effects at the Site and north of the Site. To understand the sources of U in each sampled groundwater well, a geochemical fingerprinting approach was used to define water sources to aid in understanding the source of U to the wells. Multiple lines of evidence, including general chemistry, stable isotopes, radiogenic isotopes, borehole geophysics, groundwater age dating, and multivariate statistics were used to differentiate sources of U and other associated compounds. This research has shown that combining geochemical fingerprinting, multivariate statistics, subsurface structure, and spectral gamma coupled with passive sampling (Harte et al. 2019) is an effective approach to understand the source of water and U in groundwater to wells nearby the Site. The multivariate statistics provided quantitative analyses of the data, which clustered wells into groups based on groundwater chemistry. The commonalities among the statistical approaches provide robust support for similarities among groundwater samples from sets of wells obtained by geochemical fingerprints.

In general, the wells proximal to the large tailings pile have the highest U concentration, Rn activity, gross alpha and beta, and UAR closest to 1. Most of the wells studied have U concentrations higher than the MCL of 30 µg/L and appear to be affected by regional sources of U. However, the injectate water, which has been treated and mixed with San Andres-Glorieta Formation aquifer groundwater, has the lowest U concentration. Geochemistry of the alluvial wells north of the Site may be influenced by San Mateo Creek channel sediments, although further analysis is needed to understand the mechanisms associated with this finding. Wells south of the Site have mixed groundwater sources,

likely because of the complexity of the hydrogeology and flow paths of groundwater in the aquifers.

The approach used in this study provides results that can be used by land managers and regulators to determine which wells best represent background concentrations for sites that have multiple effects from naturally occurring contaminants and anthropogenic contaminants. However, the data collected in this study are from one point in time. Seasonal geochemical variability was not assessed. Samples from wells reflect a mixture of water sources, partly from the installation of well screens or well openings (in open boreholes) that cross multiple types of units and formations (Harte et al. 2019). Installation of short-screen monitoring wells would help reduce mixing with the goal of collecting samples more representative of specific groundwater flow paths. Further research could include analyzing the chemistry of subsurface sediments, which could further define the geochemical interactions between these sediments and groundwater. In addition, sampling of more wells in the area, including those north of the Site, could provide information about the chemistry of the groundwater throughout the area. The results provide a new method to fingerprint groundwater and differentiate among water sources, which will aid regulators in decisions about background concentrations of U in groundwater near the Site and provide scientists with an additional geochemical fingerprinting approach.

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Differentiating anthropogenic sources of uranium by geochemical fingerprinting of groundwater at the Homestake Uranium Mill, New Mexico, USA.

Supplemental Information

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Sample collection, methods, and preservation

Prior to volumetric purging, the depth of the well was sounded and the water level measured from an established measurement point. For monitoring wells, three casing volumes were purged and field parameters monitored for field stabilization. For the monitoring wells without existing pumps, a variable speed submersible pump was used. For existing remedial extraction wells, residential wells in use, and select monitoring wells, the existing pumping infrastructure was used. For residential wells offline but with existing pump equipment, the well was pumped for three volumes similar to monitoring wells. During purging for all wells, physiochemical water-quality characteristics were recorded including water temperature, specific conductivity, pH, dissolved oxygen, and turbidity. Collection and preservation techniques are described in Table S1.

Constituents for chemical analyses selected to facilitate identification of water type include: alkalinity, major anions (total and dissolved), major cations (total and dissolved), selected trace elements (total and dissolved), total dissolved solids, nitrate (dissolved), gross alpha/beta, radium isotopes, radon-222, uranium isotopes and stable isotopes of deuterium (δD) and oxygen-18 ($\delta^{18}O$), sulfur isotopes of sulfur and oxygen isotopes of sulfate, nitrogen isotopes of nitrogen and oxygen isotopes of nitrate, carbon-14, dissolved gases, tritium/helium-3, chlorofluorocarbons (CFCs), and helium-4. Analyses were completed at RTI Laboratories, EPA Region 6 Laboratory, PACE Laboratories, USGS Reston Stable Isotope Laboratory, USGS Reston Groundwater Dating Laboratory, Woods Hole, and University of Utah. Analytical methods are documented in Table S1. Data were evaluated from each lab for quality control (Blake et al. 2017b). For some wells, U concentrations from RTI Laboratories were adjusted as determined by the EPA Region 6 Laboratory after methods described by Harte et al. (2018).

Multivariate technique methods

Principal component analysis (PCA) represents a transformed axis that is a linear combination of the original variables (Kimball et al. 2004) and simplifies the information into the most important factors that account for data variance. PCA can be used to systematically evaluate the geochemistry of groundwater from the wells in question and distinguishes similarities and differences among the wells. The first two principal components (PC1 and PC2) generally show enough variance in the data to differentiate groups among the samples (Kimball et al. 2004). Each chemical constituent has an associated component loading that shows the correlation between the constituent and the PCA (Kimball et al. 2004). The component loadings measure the degree to which the identified components account for the geochemical composition of the data in each well. The PCA was calculated using SigmaPlot V13.0 (SigmaPlot 2018). Within SigmaPlot, the raw data are normalized based upon a correlation matrix where each variable is standardized to have unit sample variance. The PCA is calculated using the normalized data. The PCA produces a biplot of PC1 versus PC2 and the location of the wells within this space. A 95% prediction ellipse is calculated and plotted on the biplot to show possible outliers in the distribution of data (SigmaPlot 2018).

Data variance was further evaluated by using non-metric multidimensional scaling (NMDS) and cluster analysis routines in the R packages NADA and VEGAN (Lee 2015; Oksanen and others 2016). NMDS is a non-parametric approach to PCA, that uses rank order rather than data values (Buttigieg and Ramette 2014) and produces an ordination based on distance matrix. Both PCA and NMDS produce biplots of the location of wells where samples that plot closer to each other are more similar. Cluster analysis hierarchically clusters data to

minimize the sum of squares of any two clusters (Jiang et al. 2015) and can be evaluated similarly to PCA or NMDS as the results help to distinguish similarities and differences among samples.

Table S1: Constituents, method, containers, preservatives, and holding times for analytical methods. Dissolved constituents were filtered with a 0.45- μ m filter.

[ml, milliliter; oz, ounce; C, Celsius; CFC, chlorofluorocarbon; ml, milliliter; HNO₃, Nitric acid; μ m, micrometer]

Description	Method	Container	Preservation	Holding Time
Metals	6020	250-ml plastic	HNO ₃ , 4° C	180 days
Alkalinity	SM2320B	250-ml plastic	4° C	14 days
Ammonia	SM4500	250-ml plastic	H ₂ SO ₄ , 4° C	28 days
Br, CL, F, SO ₄	300	120-ml plastic	4° C	28 days
Nitrogen	SM4500	250-ml plastic	H ₂ SO ₄ , 4° C	28 days
Gross alpha/beta	900	250-ml plastic	pH<2 HNO ₃	180 days
Radium isotopes	903.1/904	250-ml plastic	pH<2 HNO ₃	180 days
Uranium isotopes	HASL 300	250-ml plastic	pH<2 HNO ₃	180 days
Carbon-14	Liquid scintillation	500-ml polyethylene bottle	none	180 days
Radon-222	Liquid scintillation	3-40 ml vials		3 days
Stable isotopes of deuterium (δ D) and oxygen-18 (δ 18O)	Révész and Coplen (2008)	2-oz (60 ml) glass with polyseal cap	Store at ambient temperature	Months
Sulfur isotopes	Révész et al. (2012)	1-Liter polyethylene bottle	Filtered with 0.4- μ m polycarbonate membrane filter	Months
Nitrogen isotopes	Coplen et al. (2012)	4-oz (125 ml) amber polyethylene bottle	Filtered with 0.4- μ m polycarbonate membrane filter followed by a 0.2- μ m syringe filter, freeze sample	Months
He-4	Révész and Coplen (2000A and B)	3 septum glass bottles (150 ml)	4° C	3 years
Dissolved gases		copper tubing, properly sealed	none	years

Tritium/He-3		2-500 cc (16 oz) Nalgene plastic bottle)	none	years
CFCs		5-125 ml Boston round clear glass bottles with cap with an aluminum foil linear	none	30 days

Stable Isotopes of Water (δD and $\delta^{18}O$)

The δD and $\delta^{18}O$ values in the groundwater samples generally plot between the Local Meteoric Water Line (LMWL) and the Arid Meteoric Line (AML) (Figure S3). Samples T11, ND, CE7, CW37, and the Injectate plot along a reduced slope below the AML, which is indicative of fractionation due to evaporation (Langman et al. 2012). Well ND had the heaviest isotopic signature for δD and $\delta^{18}O$ values, which may indicate different source water than in other alluvial wells. In general, the middle Chinle Group wells have lighter stable isotope values, which suggests either colder temperatures during recharge or differences in source waters compared to most of the alluvial well samples (Langman et al. 2012). Well water plotting with heavier per mil (less negative) are likely experiencing some shallow recharge and affected more so by evaporation, whereas well water intercepting deeper recharge is lighter (more negative) per mil. It is likely that recharge temperatures were appreciably colder for the deeper wells suggesting mixing of some older waters. The main difference is likely the amount of shallow recharge mixing in with the wells on the bottom having the least shallow recharge. Well DD2, which is located adjacent to the western fault, has heavier stable isotope values compared to well DD, and has similar stable isotope values compared to well P3, which is located between the two faults. This pattern may indicate that the recharge to well DD2 is from both surface recharge and upwelling from deeper groundwater through the fault. The

combination of this result and the radon results in figure 7b showing DD2 with 1,500 pCi/L Rn and P3 showing 950 pCi/L Rn may suggest that groundwater at DD2 is a mixture of surface recharge water (potentially affected by the proximity to the western evaporation pond) and upwelling of water from the western fault. Well DD2 was positioned within a low-lying surface depression that may be susceptible to focused recharge and stream runoff.

Stable Isotopes of Sulfur ($\delta^{34}\text{S}$)

There is not a clear signature of mining, milling, or background based on the $\delta^{34}\text{S}$ data. Nine (CW45, CW28, CW2, CW1, ACW, CW37, Injectate, MV, and ST) of the nineteen groundwater wells analyzed for $\delta^{34}\text{S}$ had values ranging from -5‰ to 5‰, which is the $\delta^{34}\text{S}$ range identified from water in tailings ponds and groundwater near uranium mill sites in the Grants Mineral Belt and Navajo Nation (Kamp and Morrison 2014) (Figure S4). The middle and lower Chinle Group wells that plot within -5‰ to 5‰ do not show corresponding mill fingerprints as seen with the UAR, which may indicate that the Chinle Group groundwater is mixed with alluvial water or that the $\delta^{34}\text{S}$ signatures of these wells are indicative of sulfur in the surrounding geology (Ries, 1982; Karim and Veizer 2000). Groundwater from wells Q, DD2, DD, P3, CW50, and CW15 have more negative $\delta^{34}\text{S}$ values than from other wells, that may indicate mine discharge or contact with sulfides in the alluvium and Chinle Group (Figure S4). Data from the Arroyo del Puerto mine discharge and Ambrosia Lake mill site show a range of $\delta^{34}\text{S}$ from -28.4‰ to +10.4‰ (Ries 1982), which encompasses nearly all of the $\delta^{34}\text{S}$ results for the wells. Sedimentary sulfides, typically the mineral pyrite, have a $\delta^{34}\text{S}$ range -50‰ to 10‰ but most values are negative (Karim and Veizer 2000); pyrite in sandstone-type uranium deposits in the Grants Mineral Belt has a $\delta^{34}\text{S}$ range of -27‰ to -1.8‰ (Jensen 1963). However, the differences in $\delta^{34}\text{S}$ between ST, T11, CE7 and P3, CW50, DD2, DD, Q is approximately 20 per

mil, which may indicate different sources of SO_4 . For instance, the Ambrosia Lake mill site used sulfuric acid during mill processes (Ries 1982) and the Homestake mill site used alkaline leaching (Nuclear Regulatory Commission 1981). The oxidation of pyrite contained in mill tailings may result in the release of sulfuric acid, which could also be a signature of mill sites (Landa 1980).

Well T11 and CE7 have the highest SO_4 concentrations, which can be associated with the proximity to the uranium tailings piles (Ries 1982). In addition, there is clear cutoff between the dissolution of sulfate minerals compared to the oxidation of sulfate minerals around -8‰, which may be a control on U mobility. Availability of pyrite and sulfur oxidation can impact U mobilization by oxidation of U(IV) to U(VI) thereby mobilizing U(VI) (Basu et al. 2015).

Age Dating

Chemical and isotopic constituents that have been released into the atmosphere at unique rates and interact with atmospheric water may be introduced to the groundwater and can be used to estimate the apparent age of groundwater (Plummer and Friedman, 1999). Tritium (^3H) is a short-lived radioactive isotope of hydrogen, with a half-life of 12.32 years (Lucas and Unterweger 2000). These ^3H concentrations from nuclear weapons testing continue to be present in some groundwater and may be used to qualitatively constrain the recharge date (Clark and Fritz, 1997). These methods are good for dating groundwater with an age of less than 100 years. The refrigerant CFC-12 was the first chlorofluorocarbon produced, and its presence in groundwater indicates that recharge occurred after 1940. The presence of CFC-11 indicates that recharge occurred after 1945, and the presence of CFC-113 indicates that recharge occurred after 1965 (Bartolino 1997). The “Montreal Protocol on Substances that Deplete the Ozone Layer”

was established in 1996 to stop CFC production in industrialized countries (Plummer and Friedman, 1999). Since then, CFC concentrations in the atmosphere have leveled off or slightly declined (Plummer and Friedman 1999). Groundwater age is estimated from CFC data by comparing concentrations of CFCs in groundwater to the historical atmospheric concentrations of CFCs. As with most chemical tracers, biochemical processes can influence the concentrations of CFCs in groundwater. For instance, CFCs, particularly CFC-11, may be lost because of microbial degradation, leading to an older estimate of age. Other assumptions and factors that can affect the interpreted age include the temperature of the water table during recharge, the thickness of the unsaturated zone, the entrapment of excess air, uncertainty of recharge elevation, and the mixing of younger and older water in the aquifer (Plummer and Friedman, 1999). Introduction of atmospheric air during sampling will produce a younger CFC model date. Sampling methods for this study were designed so that there was little to no introduction of atmospheric air during sampling.

Carbon-14 is created in the upper atmosphere when cosmic rays interact with atmospheric nitrogen (Robertson et al. 2016). With a half-life of 5,730 years, carbon-14 can be useful to identify the age of water in an age range not covered by the other techniques used in this study.

Groundwater Travel Time (^3H and CFC)

Age differences from age dating of groundwater samples (Table S2) can be used to infer travel times if flow paths can be delineated. Groundwater in the alluvium valley between well Q and MV flows longitudinally (northeast to southwest) along the west part of the valley from well

Q (upgradient) to MV (downgradient). While groundwater flow is three dimensional, in its simplest form it can be approximated as one dimensional.

A one-dimensional rate of groundwater velocity was calculated of approximately 1 ft/d (feet/day) from age differences in tracer data of ^3H between wells Q (upgradient) and MV (downgradient) and a linear distance calculated from x and y coordinates of the wells. A minimum age difference from ^3H of 27 years is likely given that well MV had an age of at least 60 years from 2016 (sample date) and well Q had an age date of 33 years from 2016. The difference in time over the linear distance equals approximately 27 years/9,835 feet or 1 ft/d. Graphically the time and distance is represented as a sloping line in Figure S5. Representing time distance as a linear line assumes that negligible recharge from the land surface (either precipitation and surface runoff) or negligible upwelling occurs from the Chinle between the two wells.

Well DD, which is located between Q and MV, had a ^3H date younger than well Q (Figure S5). We hypothesize this to be the result of mixing of dissolved gases from Chinle waters such as helium that can affect age calculations for ^3H . The average CFC age for CFC-11 and CFC-113 was 1976 at well DD. The projected line for age at that location is 1973 (difference of 3 years).

To confirm the reasonableness of one-dimensional travel times, a simple substitution into the one-dimensional Darcy equation (eq1) can be done to check the horizontal hydraulic conductivity (HK) of the alluvium.

$$\text{Velocity} = \text{travel time} = \text{HK} \cdot I / n_e \quad (1)$$

where n_e = equivalent porosity=0.25,

I = hydraulic gradient (Head difference between well Q and MV) divided by distance = 0.0048 ft/ft,

HK = horizontal (longitudinal) hydraulic conductivity,

Head difference = 6,551.52- 6,504.68, measured in May, 2016. Q head = 6551.52 ft and MV head = 6504.68 ft,

Distance = 9,835 FT (USED X,Y CORDINATES)

Inaccuracies in use of Equation 1 include time-varying hydraulic gradients, one-dimensional approximation to flow, assumption of a homogeneous and isotropic alluvium, and assumption of a uniform porosity. Using current hydraulic-head measurements to calculate hydraulic gradients may not be representative of historical gradients.

Solving (eq 1) for HK yields a bulk value of 52 ft/d. The average HK from solution of the steady-state radial flow equation and single well pump analysis using methods described by Harte (2017) is 9.5 ft/d for the 6 alluvial wells with hydraulic data from sampling of the wells. While a 5-fold difference in HK results, a solution within an order of magnitude is considered reasonable given that heterogeneity within the alluvium can cause preferential transport and quicker flows. Based on the average HK from the single well test (lower value than the travel time estimate), it suggests the potential for some younger waters mixing into the alluvium between wells Q and MV; otherwise, the time of travel would be longer based on the lower estimate of HK from single-well pump tests.

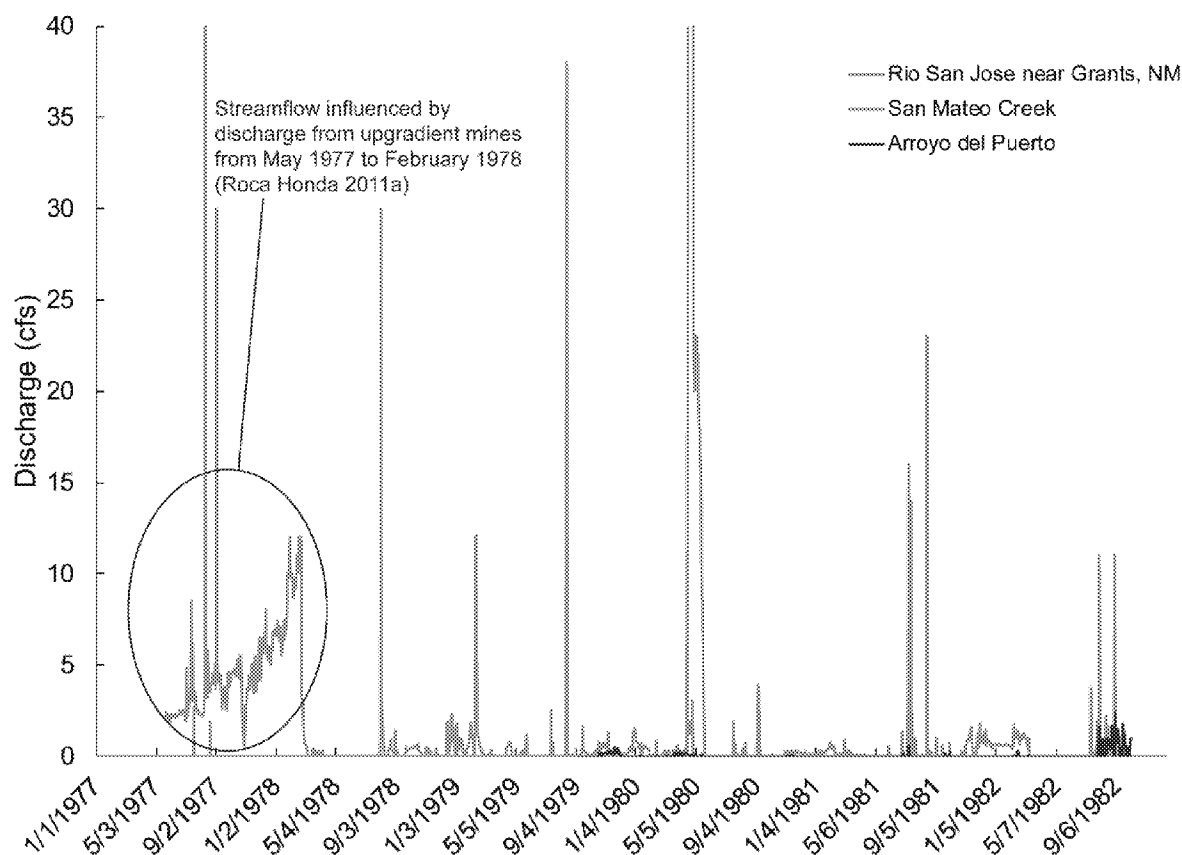


Figure S1. Discharge from USGS streamgaging stations for Rio San Jose near Grants, NM (USGS 0834300), San Mateo Creek nr San Mateo, NM (08342600), and Arroyo del Puerto nr San Mateo, NM (USGS 08342700). (cfs; cubic feet per second)

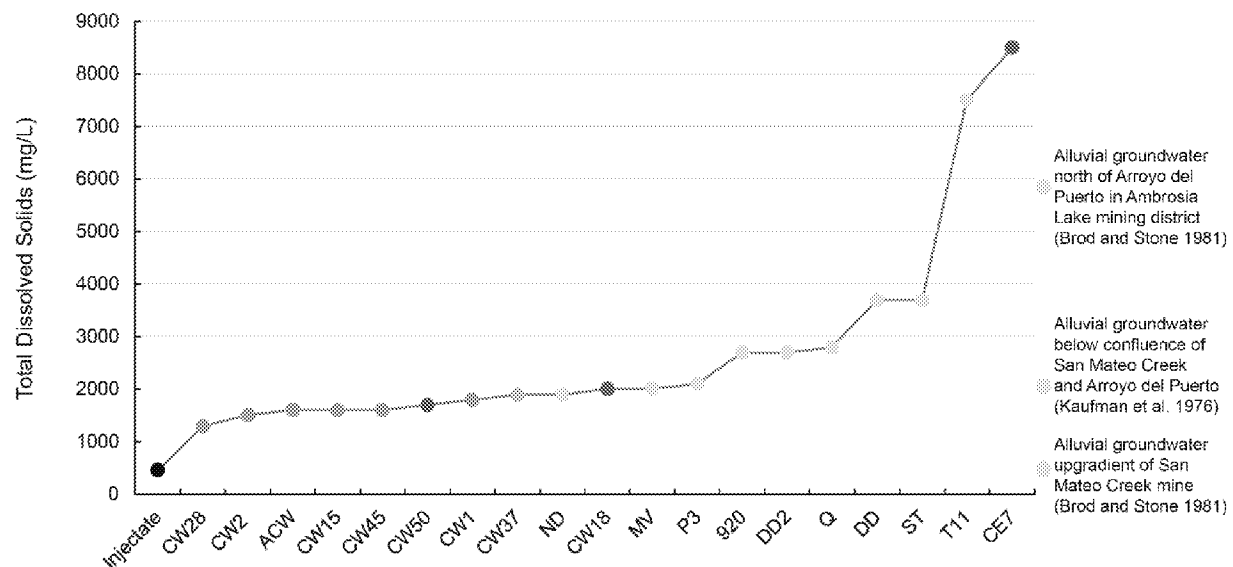


Figure S2. Total dissolved solids of water from alluvial and Chinle Group wells. Concentrations of total dissolved solids from alluvial groundwater upgradient of the Site are shown. (mg/L; milligrams per liter). Yellow circles are alluvial wells, green circles are Middle Chinle Group wells, orange circles are Upper Chinle Group wells, and the black circle is the Injectate..

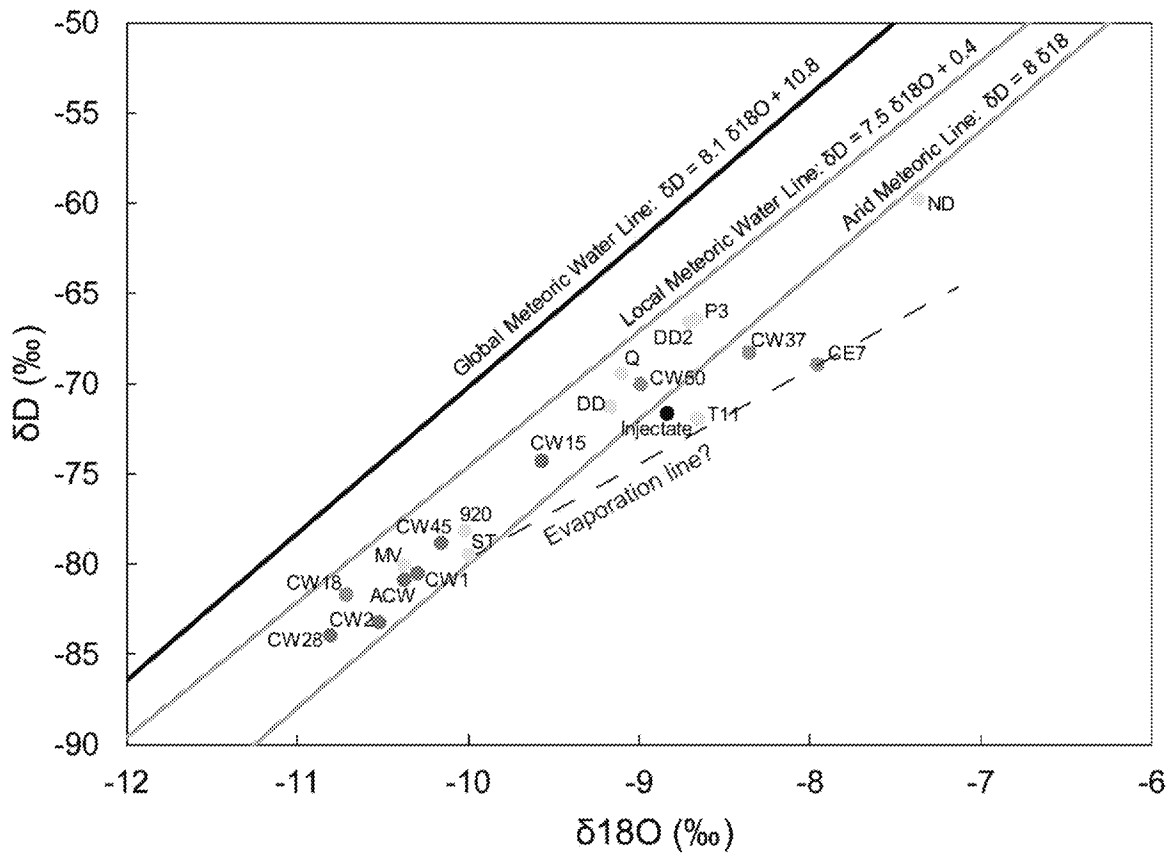


Figure S3. Plot of stable isotopes of water (δD and $\delta^{18}\text{O}$). The global meteoric water line, local meteoric line, and arid meteoric line are shown (Robertson et al. 2016). A potential evaporation line is plotted with a dashed line. (δD ; deuterium; $\delta^{18}\text{O}$, oxygen 18; ‰, per mil in parts per thousand enrichments or depletions relative to a standard of known composition Yellow circles are alluvial wells, green circles are Middle Chinle Group wells, orange circles are Upper Chinle Group wells, and the black circle is the Injectate.

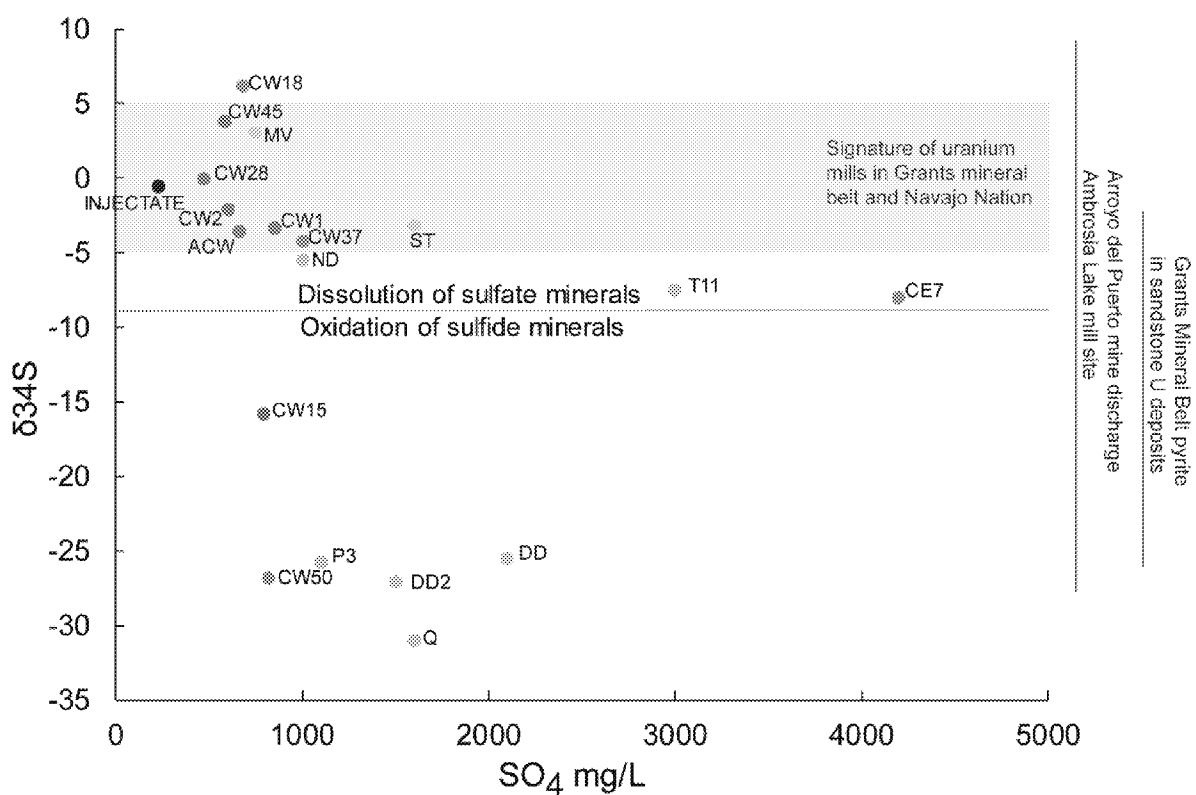


Figure S4. Plot of $\delta^{34}\text{S}$ vs. SO_4 . Known $\delta^{34}\text{S}$ ranges are shown. ($\delta^{34}\text{S}$, sulfur 34 isotope in per mil; mg/L, milligrams per liter). Yellow circles are alluvial wells, green circles are Middle Chinle Group wells, orange circles are Upper Chinle Group wells, and the black circle is the Injectate.

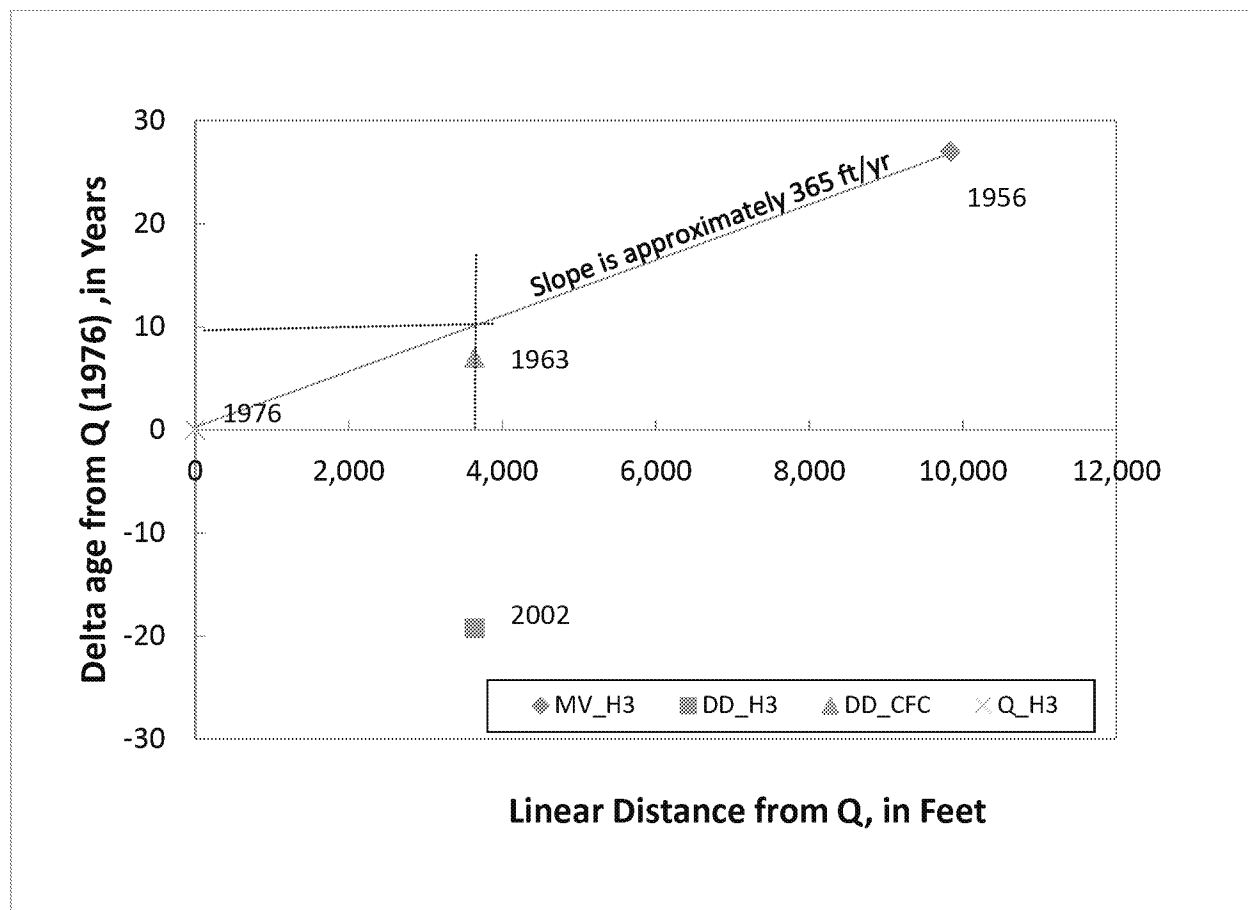


Figure S5. The time and distance from Well Q shown graphically as a sloping line. (Well Q is located at 0 distance)

Table S2. Modeled age dating results for tritium (³H) and chloroflourocarbons (CFC). Modeled ages calculated as described by Plummer and Friedman (1999).

Tritium					CFC				C-14			
Sample ID	Tritium Units	1-sigma error +/-	Calculated_Age(yr)_N_e_only_model	Calculated_Age(yr)_E_A_model	Sample ID	CFC-11_Recharge_year	CFC-12_Recharge_year	CFC-113_Recharge_year	Sample ID	Type	Fraction Modern	Fraction Modern error
CW15	0.25	0.12	>60	>60	CW2	1952.5	1978	1970	P3	DIC	0.7271	0.0015
CW18	0.53	0.05	>60	>60	CW2	1950	1976.5	1943	DD2	DIC	0.4041	0.0011
CW37	2.21	0.20	not reporting/poor fit	not reporting/poor fit	CW2	1951.5	1978	1966				
DD	5.75	0.23		13.79	CW2 Rep	1948.5	1977	1943				
CW50	0.46	0.03		39.06	CW2 Rep	1950	1978	1943				
Q	3.23	0.15		33.08	CW2 Rep	1950.5	1975.5	1943				
MV	0.64	0.03	>60	>60	CW50 Rep	1950	1967	1970				
CW2	0.09	0.05	>60	>60	CW50 Rep	1947.5	1953.5	1958.5				
CW2 - Replicate	0.01	0.01	>60	>60	CW50 Rep	1953	1955	1943				
ND	0.77	0.10	-25.15	2.24	CW50	1951	1954.5	1943				
DD - Replicate	5.90	0.37	not reporting/poor fit	not reporting/poor fit	CW50	1956	1963.5	1969.5				
CW50 Replicate	-	-	no data	no data	CW50	1951	1955	1943				
T11	-	-	no data	no data	CW15	1958	#N/A	1971				
Injectate	-	-	no data	no data	CW15	1956.5	1966	1969.5				
					CW15	1961	1967	1973				
					DD	1970.5	#N/A	1981.5				
					DD	1971	#N/A	1982.5				
					DD	1970.5	#N/A	1980				
					Homestake	1963.5	1971.5	1967.5				
					Homestake	1967.5	#N/A	1972				
					Homestake	1966	1971	1972.5				
					DD Rep	1969.5	#N/A	1981				
					DD Rep	1970	#N/A	1979.5				
					DD Rep	1969	#N/A	1978.5				
					ND	1975	1976	1983.5				
					ND	1975.5	#N/A	1985.5				
					ND	1974	1981.5	1985				

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USA, www.systatsoftware.com.

Message

From: Becher, Kent [kdbecher@usgs.gov]
Sent: 7/2/2019 8:22:00 PM
To: Purcell, Mark [purcell.mark@epa.gov]
CC: Blake, Johanna MT [jmtblake@usgs.gov]; Harte, Philip T [ptharte@usgs.gov]; Appaji, Sairam [appaji.sairam@epa.gov]; Kent Becher [kdbecher@usgs.gov]
Subject: HS journal article
Attachments: Blake 2019 EES Differentiating Anthropogenic and natural sources of U by geochemical fingerprinting of GW at the Homestake U mill.pdf

Hi Mark,

Johanna just received word that the article is published. Yeah! Here is a copy of the manuscript.

As Johanna mentioned we would like to offer up to meet with the community group to answer any of their questions and also use that meeting as a tool to help fine tune a fact sheet that covers both article.

I will be in Reston next week, but I will be back in the office the following week.

I hope all is well with you.

Thanks.

Kent Becher
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Grants Mining District, New Mexico

2015-2020 Five-Year Plan To Assess and Address Health and Environmental Impacts of Uranium Mining and Milling

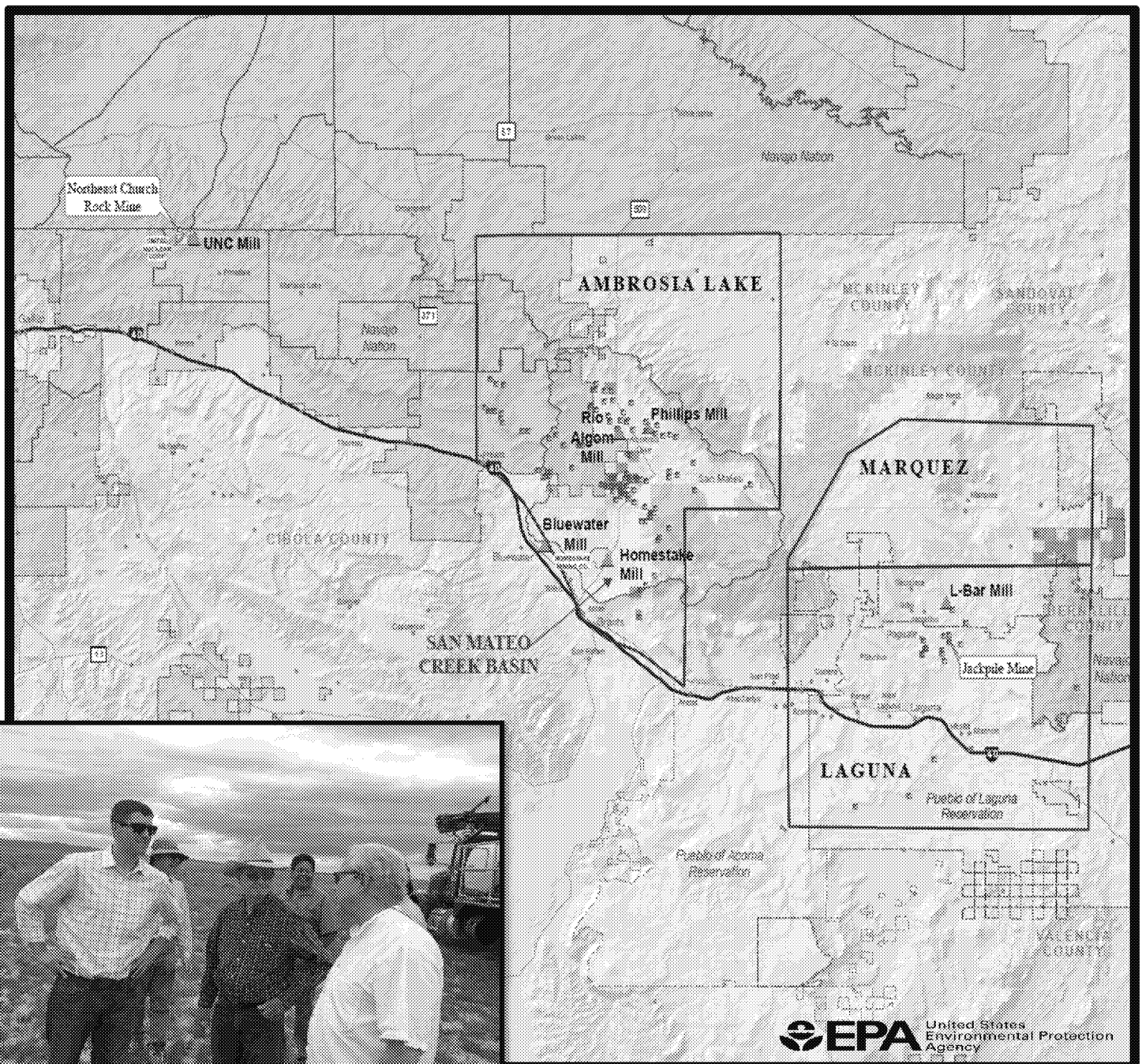


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Purpose

The purpose of this 2015 – 2020 Five-Year Plan is to report to the public the progress made in implementing the 2010 Five-Year Plan and to memorialize priorities and activities for the next five years in the Grants Mining District. The plan is intended to promote and advance the assessment and cleanup, when warranted, of contamination caused by legacy uranium mining and milling operations.

The five objectives for the 2015 Five-Year Plan are designed to guide the endeavor in the Grants Mining District. Each objective identifies goals with specific actions to be taken by those agencies with the authority and responsibility in the next five years. Although the objectives are presented as standalone subjects in the plan, they are intertwined. The objectives are:

1. Assess water supply sources for contamination
2. Assess and cleanup legacy uranium mines
3. Assess, cleanup, and perform long-term management of former uranium milling sites
4. Assess and clean up contaminated structures and properties
5. Communicate and coordinate with communities

Partners

Federal, state, and tribal governmental agencies are partners to the plan. They are committed to continue to assess and address legacy contamination and to eliminate, reduce or manage risks to human health and the environment.

The Governmental partners participating are:

- U.S. Environmental Protection Agency – Region 6
- U.S. Department of Energy – Office Legacy Management
- U.S. Department of the Interior – Bureau of Land Management
- U.S. Department of Health and Human Services – Agency for Toxic Substances and Disease Registry
- U.S. Nuclear Regulatory Commission
- U.S. Department of Agriculture – Forest Service
- Pueblo of Acoma Environment Department
- Pueblo of Laguna Environmental and Natural Resources Department
- New Mexico Environment Department
- New Mexico Energy, Minerals, and Natural Resources Department – Mining and Minerals Division
- New Mexico Department of Health

Background

The Grants Mining District is an area of significant uranium-bearing rock approximately 100 miles long and 25 miles wide encompassing portions of McKinley, Cibola, Sandoval and Bernalillo counties and organized into three sub-districts (Ambrosia Lake, Laguna, and Marquez – Figure1). These mining sub-districts contain 97 legacy uranium mines and five former uranium mill and tailing disposal sites that were active during the Atomic Energy Commission uranium purchase years (1940's-1970) and beyond until the 1990's. Over 52 million tons of uranium ore were extracted from these mines, constituting approximately 68% of the total uranium ore mined in the United States.

Land ownership within the Grants Mining District consists of public, tribal, and private property. Though surface and underground mining was prolific during the Atomic Energy Commission uranium purchase years (1940's-1970) and beyond until the 1990's, the state of New Mexico has specifically identified 97 uranium mines that require assessment and possible cleanup. The mines had reportable ore production and surface expression post mining (i.e., waste rock piles, vents/shafts, physical remnants, etc.).

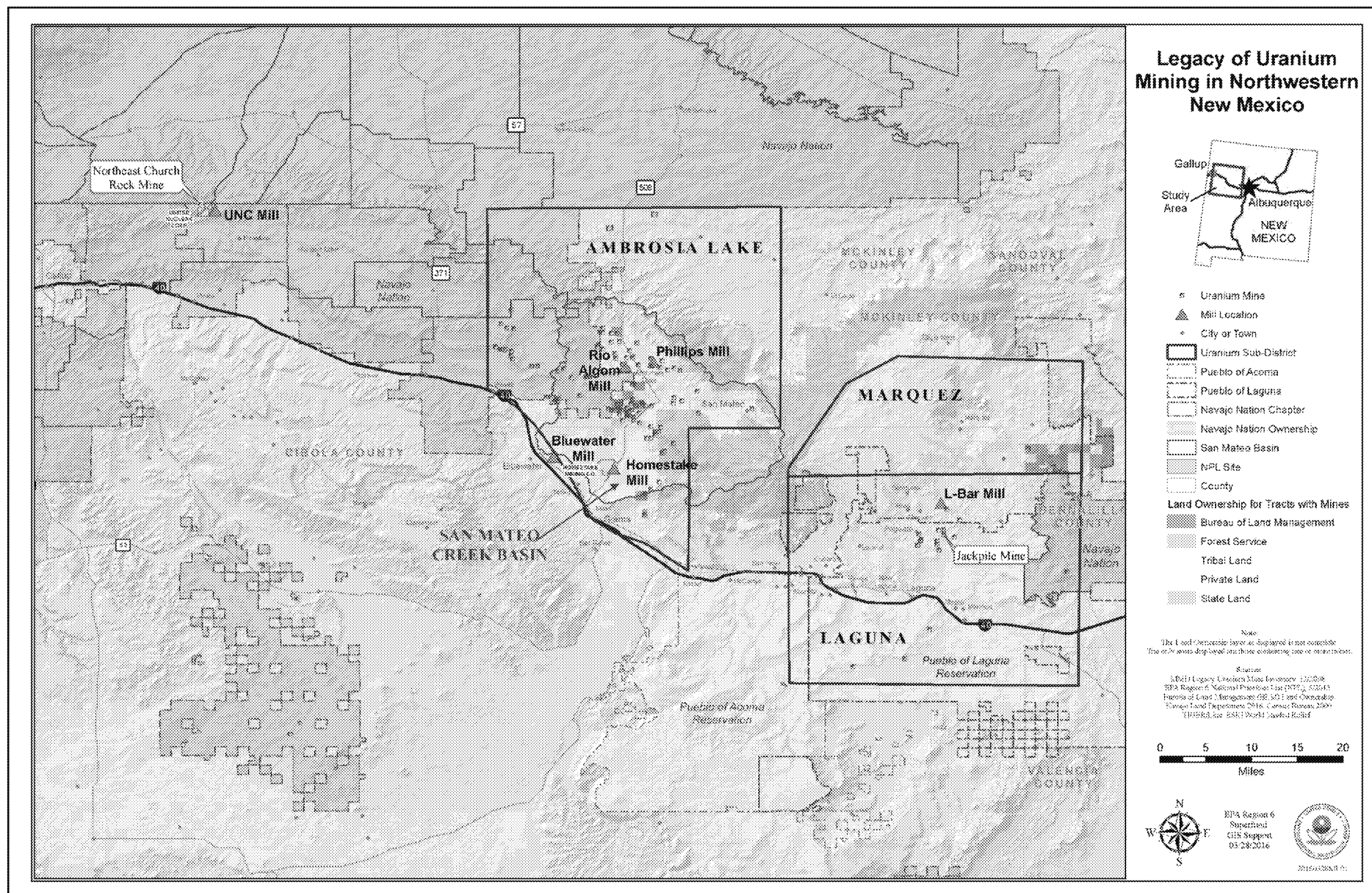


Figure 1

Summary of Work Completed 2010-2015¹ and Planned for 2015-2020

2010 – 2015 Plan		2015 – 2020 Plan
Goals	Accomplished	Goals
<u>Water Supply Sources</u> <ul style="list-style-type: none"> Evaluate private well groundwater quality Evaluate public water supplies 	<ul style="list-style-type: none"> 32 private wells sampled (2009 & 2010) <ul style="list-style-type: none"> 23 wells exceed drinking water standards for at least one or more constituents 43 private wells sampled (2014 & 2015) <ul style="list-style-type: none"> 26 wells exceed drinking water standards for at least one or more constituents 3 Milan public water supply wells sampled <ul style="list-style-type: none"> all wells meet drinking water standards 	<ul style="list-style-type: none"> In 2016, issue EPA and NMED Groundwater Assessment Reports In 2018, issue conceptual site model; a tool to understand impacts of legacy uranium mining and milling on surface water and groundwater systems in San Mateo Creek Basin
<u>Legacy Uranium Mines</u> <ul style="list-style-type: none"> Compile existing information Assess mine impact areas Evaluate Jackpile for NPL 	<ul style="list-style-type: none"> 97 mines assessed <ul style="list-style-type: none"> aerial gamma survey screening assessments 10 investigations – Dysart #2, John Bully, Johnny M, Marquez, Mary #1, Sandstone, Sections 10,12,15,30 1 cleanup – San Mateo Mine Jackpile on National Priorities List December 2013 	<ul style="list-style-type: none"> In 2016, engage potential responsible parties In 2016, BLM complete cleanup at four mines (Spencer and Barbara J Complex) In 2016, USFS complete cleanup at four mines (Old La Jara, Taffy, Vallejo, Zia) In 2016, EPA complete assessment on two mines and begin cleanup (Sections 35, 36); initiate assessment on four mines (Sections 10, 22, 24, 30W) In 2017, complete assessment on four mines and begin cleanup (Sections 10, 22, 24, 30W); initiate assessment on four mines (Sections 17, 19, 30, 33) In 2019, complete cleanup of three mines (Sections 35, 36, Johnny M) In 2020, begin cleanup of four mines (Sections 17, 19, 30, 33) Conduct remedial investigation/feasibility study at Jackpile

¹ For a more complete description of history and work accomplished under the 2010 Five-Year Plan, see Appendix A.

Summary of Work Completed 2010-2015² and Planned for 2015-2020

2010 – 2015 Plan		2015 – 2020 Plan
Goals	Accomplished	Goals
<u>Former Uranium Mills</u> <ul style="list-style-type: none"> – Surveillance and maintenance – Additional groundwater studies 	<ul style="list-style-type: none"> – Inspected and maintained disposal cells (Phillips Mill, Bluewater Mill, L-Bar Mill) – Demolished all remaining structures at the Rio Algom Mill site – Installed 10 new monitoring wells at the Bluewater Mill; additional constituents/more frequently sampling of wells at the Bluewater and Rio Algom Mill sites <ul style="list-style-type: none"> • better understanding of hydrology 	<ul style="list-style-type: none"> – Maintain disposal cells (Phillips Mill, Bluewater Mill, L-Bar Mill) – In 2017, complete groundwater feasibility study for United Nuclear Corporation – Northeast Church Rock site and update the Record of Decision to account for current site conditions – In 2017, complete investigation at Homestake Mill site and issue final groundwater and tailings pile Record of Decision – 2020 NRC license termination at Rio Algom site; handoff to DOE for surveillance and maintenance – 2020 NRC begins handoff transition to DOE
<u>Residential Areas</u> <ul style="list-style-type: none"> – Identify contaminated structures – Identify contaminated properties 	<ul style="list-style-type: none"> – Initial mission completed with 900 structures and properties assessed <ul style="list-style-type: none"> • 772 found below action levels, owners informed • 128 found above action levels and cleaned up 	
<u>Public Health Surveillance</u> <ul style="list-style-type: none"> – Study uranium exposure 	<ul style="list-style-type: none"> – Completed biometric study³ <ul style="list-style-type: none"> • six to nine times higher uranium in urine than national average 	
<u>Communication</u>	<ul style="list-style-type: none"> – Four Community meetings held – Five -Year Plan updated twice 	<ul style="list-style-type: none"> – Clearly communicate ongoing and planned actions/activities – Provide information the community needs

² For a more complete description of history and work accomplished under the 2010 Five-Year Plan, see Appendix A.

³ Grants Mineral Belt Uranium Biomonitoring Project Summary, March 2011.

OBJECTIVES

The objectives of the 2015-2020 Five-Year Plan are designed to comprehensively assess and cleanup, when warranted, contamination related to legacy uranium mining and milling activities within the Grants Mining District.

Objective 1: Assess Water Supply Sources for Contamination

Background

Residents within the Ambrosia Lake and Laguna mining sub-districts primarily rely on private and community wells for residential-domestic, stock-watering, and agricultural uses. Legacy uranium mining and milling operations generated liquid wastes (effluent). The effluents included groundwater produced from mine dewatering, process waters from unlined on-site ore leach pads, evaporation and tailing ponds, heap- and isotope-leaching, and uranium milling operations. These effluents were discharged to ground surface or surface drainage features (e.g., arroyos, channels) and allowed to infiltrate and recharge the shallow alluvium directly or via impoundment infiltration and overflow. From 30 years of mining operations alone, approximately 80 billion gallons of mine water was extracted from the subsurface and discharged to surface drainages, the majority being discharged into the San Mateo Creek Basin. The effluent discharges that occurred prior to the establishment of state and federal groundwater regulations had little or no treatment prior to discharge. The effluents discharged during legacy uranium site operations, as well as subsequent runoff from contaminated soil and sediment which continues to the present, may impact regional bedrock drinking water aquifers and shallow alluvial aquifers. These aquifers are accessed by scattered private residences and nearby municipal or community water supply systems. Additionally, extensive dewatering of underground workings during mine operations created a regionally-extensive cone of depression into which oxygenated groundwater currently is flowing. The oxygenated groundwater may dissolve and mobilize unmined uranium and associated constituents within the aquifers.

Current Status

Groundwater quality investigations have been ongoing in the San Mateo Creek Basin by the New Mexico Environment Department (NMED) and the U.S. Environmental Protection Agency (EPA), focusing on private water wells and municipal or community supply wells. Even though these investigations throughout the years have occurred as separate events, all information gathered furthers the understanding of the water systems and the potential impact from uranium mining and milling operations.

New Mexico Environment Department

The New Mexico Environment Department (NMED), under a Cooperative Agreement with the U.S. Environmental Protection Agency (EPA), conducted Phase I and Phase II Site Inspections (SIs) of the San Mateo Creek Basin groundwater from 2009 to 2012 to

determine groundwater quality in private water wells within the basin⁴. There was concern that legacy uranium mines and mills may have contributed to the widespread degradation of groundwater quality within the basin. Additionally, groundwater in the alluvial aquifer upgradient of the Homestake Mining Company Mill Superfund site was found to contain uranium and other contaminants at concentrations above federal and state drinking water standards. The results of the Phase I and Phase II SIs showed elevated concentrations of constituents in 31 of the 32 wells sampled with respect to health-based or aesthetic (color, odor, or taste) drinking water standards. The one well with water quality that did not exceed drinking water standards is not located in an area that was mined or where milling operations were located. All well owners were notified by letter of the analytical results.

In 2014, the NMED collected 26 additional groundwater samples from private and public water supply wells in the Homestake Mining Company Superfund site area at the request of the community. A report summarizing the groundwater quality will be completed in the spring of 2016 documenting the results.

U.S. Environmental Protection Agency

In 2013, the EPA, with assistance from the NMED and the U.S. Geological Survey, initiated a phased groundwater investigation for the San Mateo Creek Basin as part of an Expanded Site Inspection (ESI) to assess the nature and extent of contamination in the alluvial aquifer related to legacy uranium mining and milling. The investigation was to build on the investigative work completed by the NMED for Phase I and Phase II of the SIs. Most importantly, the investigation was crafted to determine background water quality in the alluvial aquifer in the basin, i.e., groundwater that has not been impacted by legacy mining and milling activities. Therefore, beginning in the fall of 2014 and continuing into early 2015, a field team conducted seismic surveys and drilled numerous boreholes. Despite an extensive amount of drilling, background alluvial groundwater was not found within the San Mateo Creek Basin. However, five boreholes were completed as monitoring wells in an attempt to address data gaps within the basin. A total of 20 groundwater samples were collected from the new monitoring wells as well as municipal supply and private wells for analysis. An interim report summarizing the groundwater quality will be completed and shared in the spring of 2016 documenting the results.

Goals for The Next Five Years

U.S. Environmental Protection Agency

The goal is to build a conceptual site model by 2018 that can be used as a tool to understand impacts of legacy uranium mining and milling on the surface and groundwater systems in the San Mateo Creek Basin and to identify the current and potential future risks to human health.

⁴ New Mexico Environment Department. Phase I Site Investigation Report, San Mateo Creek Legacy Uranium Mines, June 2010. New Mexico Environment Department, Site Inspection Report, Phase 2, San Mateo Creek Basin Legacy Uranium Mine and Mill site Area, April 2012.

Communicate with and provide information to residents regarding groundwater quality especially from private wells with detected uranium and other constituents at concentrations that exceed federal and state drinking standards. Information about the risks and potential mitigation practices will be provided.

Specific Actions for The Next Five Years

- Collect and analyze additional groundwater samples from existing and new monitoring wells, private water wells, and water supply wells throughout the San Mateo Creek Basin, if needed, to address data gaps in assessing groundwater quality.
- Collect and analyze additional soil impacted from legacy uranium mine water discharges to determine the potential for ongoing releases to surface water and groundwater.
- Collaborate with the NMED, the U.S. Department of Energy – Office of Legacy Management (DOE) and the Nuclear Regulatory Commission (NRC) to incorporate information from the Bluewater Mill, the Rio Algom Mill and the Homestake Mill sites and collected groundwater quality information into the conceptual site model for the San Mateo Creek Basin.
- Issue the conceptual site model in 2018.

Project plans will be developed to accomplish the specific actions in coordination with all appropriate agency partners.

Potential Challenges

Natural Contamination

Since the San Mateo Creek Basin contains uranium-bearing rock formations from which groundwater is accessed by private water wells, it is challenging to determine if groundwater containing constituents that exceed federal and state water quality standards are due to natural conditions and/or has been impacted by legacy mining and milling operations. Additional analyses will be performed on groundwater samples to attempt to forensically distinguish mining and milling impacts from natural conditions.

Objective 2: Assess and Cleanup of Legacy Uranium Mine Sites

Background

Uranium mining was prolific in the Grants Mining District starting in the 1950's until as late as the mid-1980's. In the Grants Mining District alone, over 300 mining permits were issued by the state of New Mexico for mine exploration and mining operations in McKinley, Cibola, Sandoval and Bernalillo counties. The extraction of uranium-bearing ore occurred through open pits, from underground workings that were extensively connected and solution mining. Of all of the mining operations, 97 legacy uranium mines with surface expression (i.e., open pits, waste rock piles, vents/shafts, etc.) are the focus for reclamation and cleanup.

Current Status

For the 97 uranium mines in the Grants Mining District, the EPA has identified four categories with respect to entities that should be responsible for addressing the legacy mines and operational impacts.

- Mines associated with Jackpile-Paguate
- Mines with Potentially Responsible Parties
- Mines covered by the Tronox Settlement
- Mines without responsible parties (orphans)

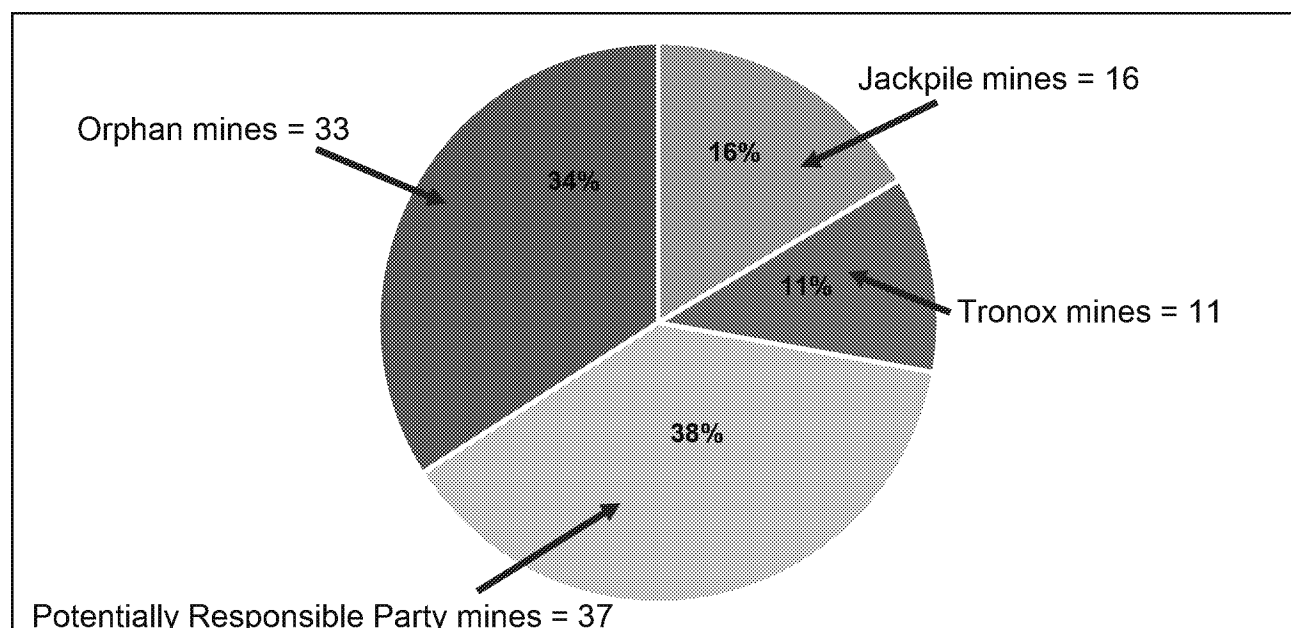


Figure 2

The Jackpile-Paguate mines are located in the Laguna sub-district on the Pueblo of Laguna. The whole mine area was added to the National Priorities List in December 2013 and will be addressed by the EPA's Remedial Program.

For the Tronox mines⁵, all of which are located in the Ambrosia Lake sub-district, the mines have been divided into three geographic sub-areas of private or State owned properties (Figure 3): East (Sections 35 and 36 Mines); Central (mines east of State Highway 509, Sections 17, 19, 30, 32, and 33 Mines); and West (Sections 10, 22, and 24, and 30W Mines).

As more information is gathered about mines with potentially responsible parties and the orphan mines, further geographic sub-areas may be identified.

From 2008 through 2014, screening assessments were conducted on the majority of the 97 legacy uranium mines in the Grants Mining District by the various Agencies and some actions were taken. Specifically, the U.S. Forest Service (USFS) completed a removal action which consolidated waste rock and contaminated soils at the San Mateo Mine and assessed the Taffy, Vallejo, Old La Jara and Zia Mines located in the Cibola National Forest. Additionally, the Bureau of Land Management (BLM) completed assessments on several mines located on federally managed lands and developed a removal action plan to address threats to human health or the environment.

In 2010 and 2011, the EPA conducted Airborne Spectral Photometric Environmental Collection Technology (ASPECT) overflights of the Ambrosia Lake mining sub-district to collect gamma radiological measurements. Results from the ASPECT aerial gamma surveys indicated elevated gamma radiation activity at many legacy uranium mine sites (Figure 4). The largest gamma radiation anomalies were identified at mine sites in the Ambrosia Lake area and near the village of San Mateo located near Mount Taylor that operated as wet mines with mine water discharges to ground surface. Using information from assessments and the ASPECT aerial gamma surveys, EPA conducted detailed assessments on nine mine sites likely to pose a threat to human health or the environment.

In 2011, the EPA conducted a Removal Action to relocate a resident and his livestock from property located immediately adjacent to the Johnny M Mine to address an imminent and substantial endangerment from elevated radiation. The EPA signed an Administrative Order on Consent for Removal Action with the operator of the Johnny M Mine in 2012 for performance of a site investigation and engineering evaluation/cost analysis at the mine and adjacent residential property. The site investigation was completed in early 2014 and confirmed the presence elevated gamma radiation in soil. Based on the site investigation report and engineering evaluation/cost analysis, there is an estimated 500,000 cubic yards of contaminated soil that will need to be addressed.

⁵ In April, 2014, the United States (U.S.) and the Anadarko Litigation Trust entered into a settlement agreement with Anadarko Petroleum Corporation and some of its affiliates regarding environmental liability associated with former Kerr McGee industrial and mining operations. The settlement approved by the U.S. District Court and the U.S. Environmental Protection Agency provided approximately \$984,500,000 for the cleanup of over 50 Tronox Navajo Area Abandoned Uranium Mines (Tronox NAUM) sites. Of the over 50 Tronox NAUM sites listed in the settlement, 22 mine operations on 11 mine sites are located in the Grants Mining District. The other Tronox NAUM are located on the Navajo Nation in the Cove Wash area and Eastern Agency.

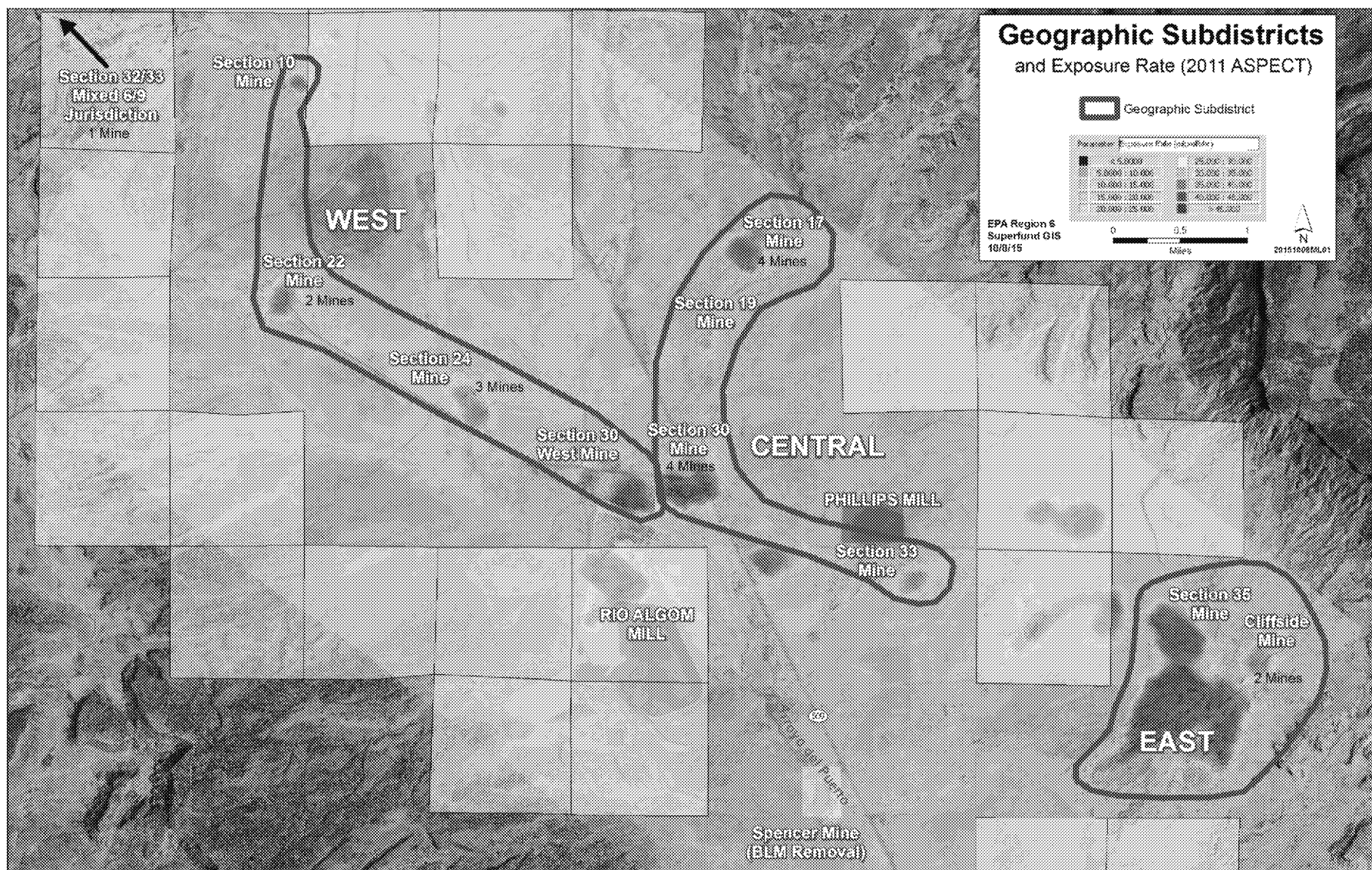


Figure 3

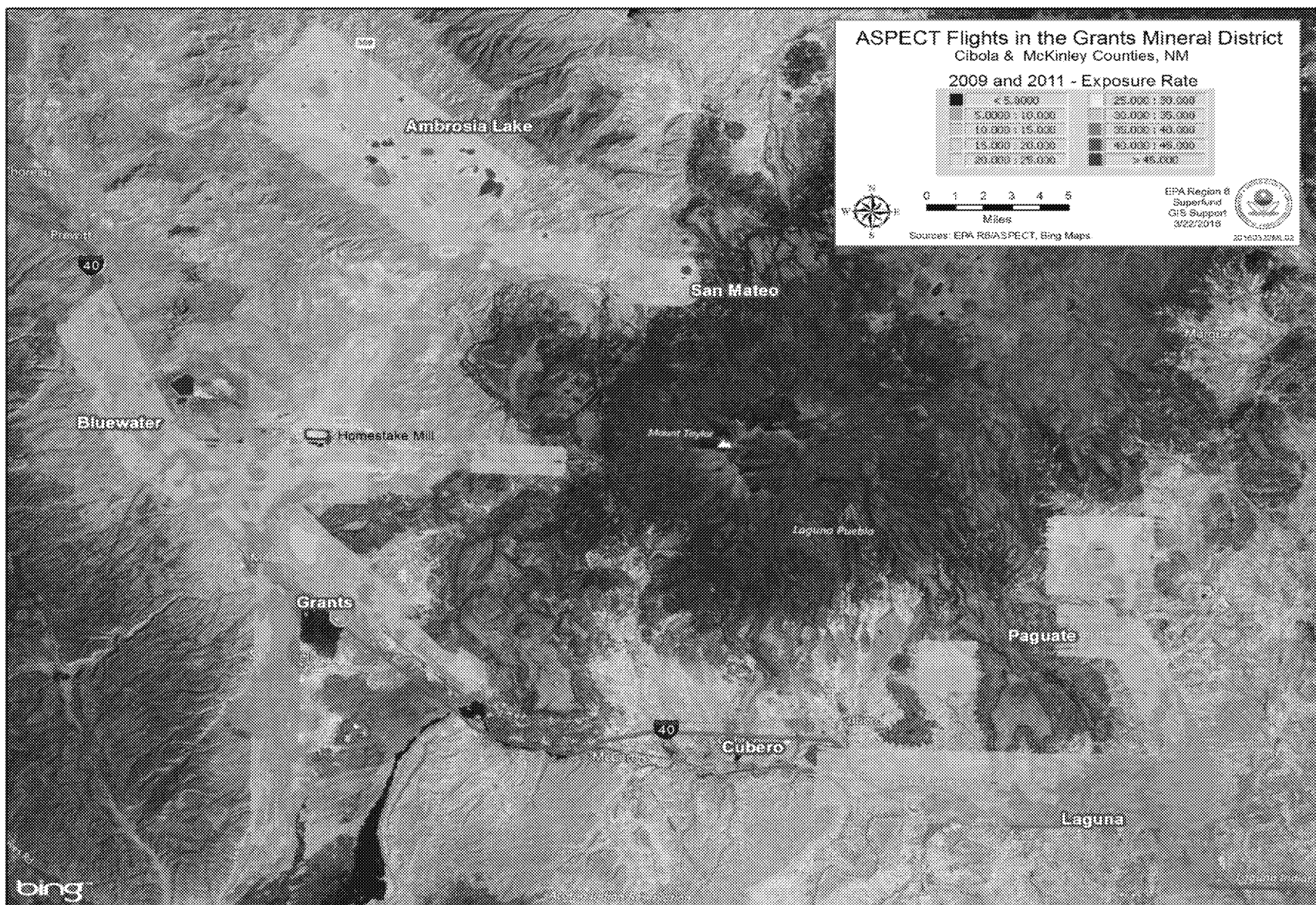


Figure 4

Goals for the Next Five Years

U.S. Environmental Protection Agency

During the next five years, the EPA will conduct a series of assessments and engineering evaluation/cost analyses at uranium mine sites for the purpose of obtaining necessary information to develop an appropriate number of investigations which will become the basis for any subsequent actions that may be necessary to abate the threats to human health and the environment posed by these mine sites.

Bureau of Land Management

The goal is to restore watersheds impacted by legacy uranium mines and mitigate hazards to protect public health and safety.

U.S. Forest Service

During the next five years, the USFS will continue to evaluate site conditions at abandoned mines with a record of uranium production on lands they manage in the Grants Mining District.

Specific Actions for Next Five years

U.S. Environmental Protection Agency

Assessments and engineering evaluation/cost analyses and potential non-time critical removal actions will be conducted and completed in the Ambrosia Lake sub-district, East geographic subarea, starting with the Section 35 and 36 mines. The assessment of the East geographic subarea will be completed in the summer of 2016 with actions completed by the end of 2019. Assessments will be completed in the West geographic subarea on all Tronox mines by 2017 with non-time critical removal actions beginning in the Central geographic subarea in 2020. Additionally, will oversee response actions at the Johnny M Mine and initiate a Remedial Investigation/Feasibility Study at the Jackpile-Paguete mines. Other mine assessments may be reprioritized, as warranted.

U.S. Bureau of Land Management

During the next five years, the BLM through the New Mexico Energy, Minerals, and Natural Resources Department's Abandoned Mine Land Program is planning on completing reclamation of the Spencer Mine and the Barbara J Complex Mines (which are comprised of three mine operations). Additionally, the physical hazards will be addressed at the Poison Canyon Mine. At the Rio Puerco Mine, reclamation activities will be conducted by the current mine operator/claimant which will include placement of mine wastes into a lined pit and removal of structures, tanks and other mine-related facilities (Figure 5).

U.S. Forest Service

Removal actions will be performed at the Taffy, Vallejo, Old La Jara and Zia Mines. These sites will be made safe for visitors and wildlife and will be restored to a natural appearance and re-vegetated with native grasses (Figure 6).

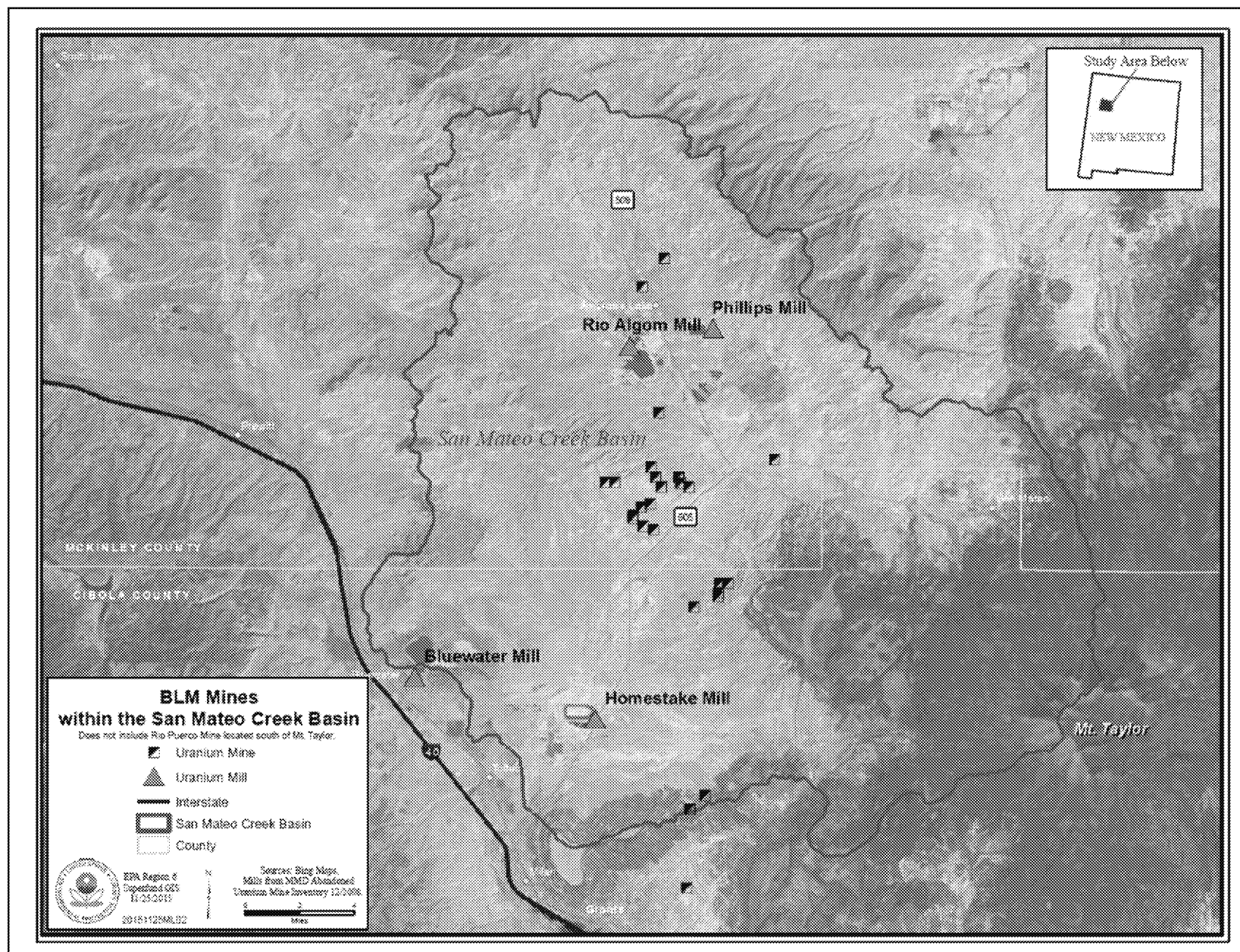


Figure 5

Opportunities for Potentially Responsible Parties

The EPA will continue its efforts to engage and work with potentially responsible parties for the assessment and cleanup of mines or to secure funding through enforcement for this work.

Selection of final cleanup plans for mines is dependent on identification of cost effective and protective solutions for mine operation related materials.

Objective 3: Assess, Cleanup, and Perform Long-Term Management of Former Uranium Milling Sites

Background

Five legacy uranium milling operations are located in the Grants Mining District. Within the San Mateo Creek Basin of the Ambrosia Lake sub-district, milling activities occurred at the Phillips Mill-Ambrosia Lake site from 1958 to 1982; at L-Bar Mill site from 1977 to 1981; at the Homestake site from 1957 to 1990; at the Anaconda-Bluewater site from 1953 to 1982, and at the Rio Algom-Ambrosia Lake site from 1958 to 2002. The Bokum Mill is located within the Marquez sub-district; however, no uranium ore was processed at the site.

The United Nuclear Corporation Mill – Northeast Church Rock Superfund (UNC–NECR) site is located outside of the Grants Mining District near Gallup, New Mexico, but is included for a more comprehensive understanding of legacy uranium operations in northwestern New Mexico.

The DOE, with NRC oversight, is responsible for long-term surveillance and maintenance duties at the Phillips Mill-Ambrosia Lake (Phillips Mill), Anaconda-Bluewater Mill (Bluewater Mill), and L-Bar Mill sites.

The NRC, in coordination with the EPA and the NMED, currently regulates ongoing remedial activities at the both the Homestake Mining Company Uranium Mill Superfund (Homestake) site and the UNC–NECR site.

The NRC also oversees reclamation in coordination with the NMED at the Rio Algom-Ambrosia Lake Mill (Rio Algom Mill) site.

The NRC current and historical licensing documents for the Bluewater, Homestake, Rio Algom, Phillips, and L-Bar Mills can be located at their electronic reading room.⁶ Documents related to the DOE's responsibility for Title I and II uranium mills are also in the NRC electronic reading room and DOE webpages.⁷

⁶ <http://adams.nrc.gov>

⁷ <http://energy.gov/lm/office-legacy-management>

Current Status of Work

The DOE reviews groundwater compliance strategies annually for the Phillips Mill, Bluewater Mill, and L-Bar Mill sites to track progress against compliance standards.

The DOE monitors activities at the Homestake and UNC–NECR sites and the Rio Algom Mill in preparation for when the sites transition from the NRC to DOE’s stewardship.

Additionally, the DOE and NRC continue to work with NMED under a Cooperative Agreement to provide the resources to review and participate in the DOE’s activities during these long-term actions.

For the Rio Algom Mill, reclamation under NRC regulation is largely complete. A radon barrier was constructed over Tailings Impoundment 1 in 1999 and the mill was decommissioned in 2005. Additional reclamation tasks were completed in subsequent years, including the construction of a 1000-year diversion channel for the Arroyo Del Puerto. In 2014 and 2015, RAML demolished all remaining structures at the mill site and consolidated remaining waste material into Tailings Impoundment 2.

The DOE conducted additional hydrogeological work at the Phillips and Bluewater Mill sites. At the Phillips Mill site groundwater monitoring of existing site wells was increased in frequency, and additional constituents were analyzed as recommended by NMED. A new monitoring well was installed in the alluvium immediately down gradient of the uranium mill tailings disposal cell to sample groundwater at the alluvium/bedrock contact. This well has been dry so no groundwater samples have been collected.

The DOE has conducted a considerable amount of work at the Bluewater site. Ten new monitoring wells were added to the original nine wells to better understand the site hydrogeology of the Rio San Jose alluvium and San Andres bedrock aquifers. Groundwater monitoring of the site well network was increased in frequency and additional constituents were analyzed as recommended by NMED. Offsite private wells have also been sampled. Additionally, disposal cell performance and the site and regional hydrogeology were evaluated to determine the extent of contamination originating from the Bluewater site. A report describing this evaluation was submitted to the NRC, NMED, and the EPA in November 2014, and is available to the public.

Goals for the Next Five Years

Legacy sites (Phillips Mill, Bluewater Mill, L-Bar Mill):

- The DOE will review and update the Bluewater Mill Site Status Report as appropriate, and evaluate the impacts of new information on the understanding of the Bluewater Mill site.
- The DOE, where applicable, continue to update sampling information from on-site monitoring wells and evaluate the impacts of new information on the groundwater activity and composition.

- The DOE work with the NMED through the Cooperative Agreement to support NMED's participation in DOE activities to ensure that former uranium mill sites do not pose risks to human health and the environment.

Ongoing remedial activities sites (Rio-Algom, Homestake):

- The DOE monitors activities at the Homestake and Rio Algom Mill sites in preparation for when the sites transition to their stewardship.
- Complete EPA Record of Decision for the groundwater and the tailings pile at Homestake.
- Update the EPA Groundwater Record of Decision at UNC–NECR site to account for current site conditions.
- NRC license termination in 2020 for the Rio Algom Mill.

Specific Actions for Next Five Years

Legacy sites (Phillips Mill, Bluewater Mill, L-Bar Mill):

During the next five years, the DOE plans to continue ongoing monitoring of the milling-activities affected groundwater at the Bluewater Mill site, as follows:

- Continue to monitor and review the condition of existing monitoring wells at Bluewater. Specifically, they will continue to sample the on-site monitoring wells annually for milling-related metals of concern and major ions and cations, and collect water level data at the wells.
- Provide on-site well monitoring data to the EPA for use in developing the conceptual model for the San Mateo Creek Basin.
- Work with the NMED through the Cooperative Agreement to test private wells off of the Bluewater Mill site that have the potential of being impacted by past milling activities at the Bluewater Mill.

Ongoing remedial activities sites (Rio Algom, Homestake):

The DOE will participate in meetings related to the Homestake and Rio Algom Mill sites and review the progress of these ongoing reclamation activities. The final licensing action will be the approval of a redesigned channel by the NRC.

Objective 4: Assess and Clean up Contaminated Structures and Properties

Background

Uranium mining or milling waste was occasionally used as sand for aggregate (in foundations and stucco) and contaminated stones were incorporated into the walls and floors of structures, including homes. Structures may also be contaminated by the presence of mined or naturally-occurring radioactive materials in outside dust and soil brought into homes on shoes and clothing. Flagstones and petrified wood have been used as decorative items in homes and in residential landscaping.

Current Status of Work

U.S. Environmental Protection Agency's Accomplishments

From 2010 through 2015, the EPA's Removal Program assessed over 900 structures and properties for gamma and elemental uranium contamination (Figure 7). All of the villages of the Pueblo of Laguna and communities of the Acoma Pueblo, the villages of Bluewater, San Mateo, and the Cebolleta Land Grant, and the subdivisions south of the Homestake Mill site were assessed. Of the 900, 772 structures were found below action levels and deemed to require no action; however, 128 of the assessed properties had soil radiation above action levels and were cleaned up. One structure was demolished and another was replaced with a modular house. One resident living in close proximity to Johnny M legacy uranium mine was relocated.

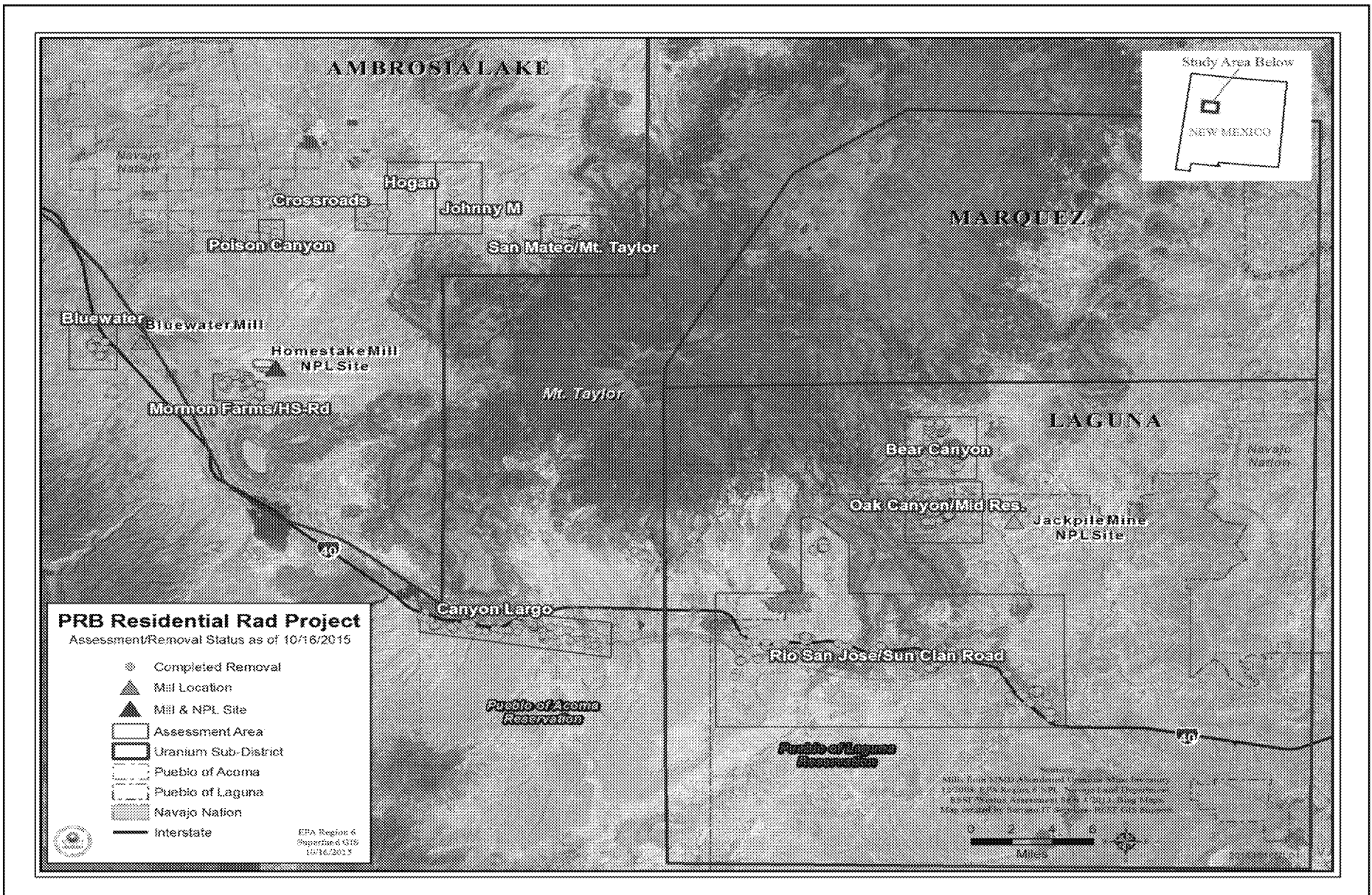


Figure 7

Goals for the Next Five Years

U.S. Environmental Protection Agency

While the EPA has completed work on all known residential properties with excess gamma radiation contamination, the EPA is prepared to work with any additional property owners to identify any potential excess gamma radiation contamination issues.

Objective 5: Communicate and Coordinate with Communities

Background

Historical releases to ground and surface water, soil and air have been documented from legacy uranium sites throughout the Grants Mining District. Releases are likely to continue, posing risk to area residents, the public, and the environment.

Current Status

In the 2010 Five-Year Plan, communication with the public, federal and state agencies, and tribes was incorporated into each of the plan objectives. For the 2015 Five-Year Plan, communication and coordination about community issues will be emphasized by separating into its own objective.

For the 2010 Five Year Plan, the EPA in cooperation with federal, state and local partners continued to provide ongoing community engagement with residents and communities. The EPA has provided and/or participated in community meetings, site technical meetings with agencies, and specific meetings with residents regarding the UNC-NECR, Homestake Mill, and the Jackpile-Paguate Mine Superfund sites. For example, EPA staff has met with the Bluewater Valley Downstream Alliance (BVDA) and the Multicultural Alliance for a Safe Environment (MASE) regarding the Homestake Mining Company Mill Superfund site to explain ongoing site remediation, met with Pueblo of Laguna leaders on the Jackpile-Paguate Mine site, and participated with the EPA Region 9 in frequent tribal and village meetings regarding the UNC-NECR site.

The EPA has also provided several community involvement support initiatives to enhance communication and outreach at these sites. Technical Assistance Services for Communities, as well as a Technical Assistance Grant were provided to BVDA and Homestake Mill site communities. A Technical Assistance Services for Communities was also recently approved for the UNC-NECR site to assist the community with a better understand of the science, regulations and policies of environmental issues associated with upcoming site cleanup issues.

Goal for The Next Five Years

The goal for the 2015 Five-Year Plan partners is to provide clear and understandable information about ongoing and planned actions and activities in the Grants Mining District. This will be accomplished through enhanced coordination amongst the partners to provide clear and understandable information that the community members request, want, and/or need.

Specific Actions for Next Five Years

- Conduct strategic outreach to residents that use groundwater exceeding federal and state drinking water standards.
- Implement education plan to increase awareness of studies, processes, regulatory involvement, and the public's right to know.
- Maintain and update the EPA's Grants Mining District website.
- Hold community meetings for Superfund sites in the Grants Mining District.
- Maintain the Field Operations and Outreach Center (FO-OC) located in the Ambrosia Lake sub-district and the Grants Mining District Post located in downtown Grants, New Mexico through this period.
- Make available Technical Assistance Services for Communities and Technical Assistance Grants.
- Annual updates to Community Involvement Plans at each of the Superfund sites in the Grants Mining District.



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Appendix A: History and Detailed Activities under 2010 Five-Year Plan

Objective 1: Assess Water Supply Sources for Contamination

Background

Groundwater in the Grants Mining District has been contaminated from legacy uranium mining and milling operations, but the current day impacts to groundwater quality at most of the legacy mine sites as well as downgradient of the mines and former mill sites on a regional scale have not been assessed. The majority of these mine and mill sites are located within the San Mateo Creek basin, a 320-square mile drainage basin north of the village of Milan. Of these mines, many were operated as “wet mines” where the underground workings were dewatered. The mine water was discharged to surface drainages and allowed to infiltrate the ground surface and percolate downward to saturate the alluvium. The discharge of an estimated 80 billion gallons of mine water from these wet mines re-saturated the alluvial sediments in the basin on a massive scale, with water levels being raised over 50 feet in some places of the basin. This massive slug of mine water has been draining out of the basin alluvium and recharging the underlying bedrock aquifers that sub crop against the alluvium for over 50 years.

There are no groundwater quality data for most of the uranium mine sites within the San Mateo Creek Basin. However, such data have been collected for several mines in the Ambrosia Lake mining sub-district under the New Mexico Environment Department’s (NMED) groundwater abatement regulations and discharge permitting program. Groundwater quality data have also been collected by the U.S. Department of Energy (DOE) at uranium mill sites that have been turned over to its Legacy Management Program for long-term maintenance and monitoring and by mill operators performing groundwater remediation or monitoring under the U.S. Nuclear Regulatory Commission’s (NRC) Source Materials License program. Additionally, groundwater quality data have been periodically collected by the NMED from private water wells and municipal or community supply wells scattered throughout the basin. These data indicate that groundwater in the shallow alluvium and bedrock formations contain uranium and other contaminants at concentrations exceeding federal drinking water standards and New Mexico groundwater standards. Furthermore, these data indicate that such contamination may be widespread throughout the basin.

Since uranium and other contaminants detected in groundwater are naturally occurring substances and the sediments which comprise the alluvium within the basin are derived in part from uranium ore-bearing formations such as the Westwater Canyon Member of the Jurassic Morrison Formation, these contaminants will be present in the groundwaters of the alluvium and bedrock formations at some natural background concentration or range of concentrations (depending on the location within the basin). This natural background concentration or range of concentrations for a contaminant would represent a baseline in which to compare concentrations from groundwaters believed to be contaminated by legacy uranium sites and, therefore, would need to be determined to define the extent of the impacts to groundwaters from the uranium sites.

Although uranium mining and milling operations occurred throughout many parts of the San Mateo Creek basin, there still may be locations within the basin where groundwater quality has not been impacted by these legacy uranium sites (e.g., upgradient of legacy mine and mill sites). At these locations, such water quality should represent natural background water quality. Without background water quality data, the extent of the impacts to groundwater from these legacy uranium sites will be difficult to ascertain.

Previous and Ongoing Regulatory Actions

New Mexico Environment Department

The NMED, under a Cooperative Agreement with the U.S. Environmental Protection Agency (EPA), conducted Phase I and Phase II site inspections (SIs) of the San Mateo Creek Basin groundwater from 2009 to 2012 to determine if groundwater quality at private water wells within the basin had been contaminated. There was concern that legacy uranium mines and mills may have contributed to the widespread degradation of groundwater quality within the basin. Additionally, groundwater in the alluvial aquifer north of the Homestake Mining Company Mill Superfund site was found to contain uranium and other contaminants at concentrations above federal and state standards. The results of the Phase I and Phase II SIs showed elevated concentrations of constituents in 31 of the 32 wells sampled with respect to health-based or aesthetic (color, odor, or taste) drinking water standards. The one well with water quality that did not exceed drinking water standards is not located in an area that was mined or where milling operations were located. All well owners were notified by letter of the analytical results.

In 2014, the NMED collected 26 additional groundwater samples from private and public water supply wells in the Homestake Mining Company Superfund site area at the request of the community. A report summarizing the groundwater quality will be completed in the spring of 2016, documenting the results.

U.S. Environmental Protection Agency

In 2013, the EPA, with assistance from the NMED and the U.S. Geological Survey, initiated a phased groundwater investigation for the San Mateo Creek basin as part of an Expanded Site Inspection (ESI) to assess the nature and extent of contamination in the alluvial aquifer related to legacy uranium mining and milling. The investigation was to build on the investigative work completed by the NMED for Phase I and Phase II of the SIs. Most importantly, the investigation was crafted to determine background water quality in the alluvial aquifer in the basin, i.e., groundwater that has not been impacted by legacy mining and milling activities. Therefore, beginning in the fall of 2014 and continuing into early 2015, a field team conducted seismic surveys and drilled numerous boreholes. Despite an extensive amount of drilling, background alluvial groundwater was not found within the San Mateo Creek Basin. However, five boreholes were completed as monitoring wells in an attempt to address data gaps within the basin. A total of 20 groundwater samples were collected from the new monitoring wells as well as municipal supply and private wells for analysis. An interim report summarizing the groundwater quality will be completed and shared in the spring of 2016 documenting the results.

Department of Energy – Office of Legacy Management

The DOE supported the Five-Year Plan by conducting additional hydrogeological work at their Ambrosia Lake-Phillips Mill and Bluewater uranium mill tailings disposal sites. At Ambrosia Lake, groundwater monitoring of existing site wells was increased in frequency, and additional constituents were analyzed as recommended by NMED. Also, a new monitoring well was installed in the alluvium immediately downgradient of the disposal cell to sample groundwater at the alluvium/bedrock contact. This well has been dry, so no groundwater samples have been collected.

A considerable amount of work has been conducted by DOE at the Bluewater site. Ten new monitoring wells were added to the original nine wells to better understand the site hydrogeology of the Rio San Jose alluvium and San Andres bedrock aquifers. Groundwater monitoring of the site well network was increased in frequency, and additional constituents were analyzed as

recommended by NMED. Offsite private wells have also been sampled. Additionally, disposal cell performance and the site and regional hydrogeology were evaluated to determine the extent of contamination.

Objective 2: Assess and Cleanup of Legacy Uranium Mine Sites

Background

The Grants Mining District was the primary location of uranium extraction and production activities in New Mexico from the 1940s to the 1990s. Three mining sub-districts located within the District – Ambrosia Lake, Laguna, and Marquez – contain an estimated 97 legacy uranium mines with recorded uranium ore production outside of the boundaries of the Navajo Nation.¹ During the mine operational period, many of the larger mines conducted extensive dewatering operations to access ore below the water table. Most effluent produced from mine dewatering operations received little or no treatment before being discharged to the ground or surface drainages during the majority of the mine operational period, causing perennial stream flows in major drainages. The extensive dewatering operations significantly changed areal hydrologic conditions, resulting in continuing influx of oxygenated groundwater to areas that were dewatered during the mine operational periods. Impacts to groundwater from these discharges were noted both in a 1975 EPA document titled “*Summary of Ground-Water Impacts of Uranium Mining and Milling in the Grants Mineral Belt, New Mexico*” and a 1986 New Mexico Environmental Improvement Division (predecessor agency of NMED) document. Other environmental impacts may have been caused by erosion and leaching of mine waste materials, some of which were deposited in arroyos where it remains to the present-day, and by the reported operation of on-site heap-leach and stope-leaching operations. Few of the legacy uranium mine sites have undergone surface reclamation, and many have physical hazards that remain such as open adits and shafts, as well as uncontrolled waste rock and ore piles on-site.

Previous and Ongoing Regulatory Actions

New Mexico Environment Department

Within the Ambrosia Lake Sub-District (ALSD), the NMED completed preliminary assessments of the Poison Canyon Mining District in the late 1980s, a preliminary assessment in 1991, a preliminary assessment addendum in 2008 of the Febco Mine, a preliminary assessment of the Silver Spur Mine in 2008, a hazard ranking package in 1984 for the Haystack Mining District, and a preliminary assessment in 1988 of the San Mateo Mine. Additionally, in 2008 the NMED completed a preliminary assessment of the San Mateo Creek Basin, which is located within the ALS and where the majority of the legacy uranium mine and mill sites are located. In the Laguna Mining District, the NMED completed a preliminary assessment of the St. Anthony Mine in 1995.

From 2009 through 2012, the NMED completed pre-Comprehensive Environmental Response, Compensation, and Liability Information System (CERCLIS) screening assessments for 66 legacy uranium mines on behalf of the EPA. Pre-CERCLIS screening is the process for reviewing data on a potential site to determine if it may warrant response actions under CERCLA. Of the 66 sites screened, 51 sites were recommended for further CERCLA response actions by the NMED. No further response actions were recommended for the remaining 15 sites at the time of the screening because remediation and reclamation activities were being conducted by the owner/operator in accordance with New Mexico Water Quality Control Commission regulations under an abatement plan and the New Mexico Mining Act under a closeout plan. The NMED and

¹ Legacy uranium mines that are located on lands within the boundaries of the Navajo Nation are being addressed in detail in the 2014 Federal Actions to Address Impacts of Uranium Contamination in the Navajo Nation Five-Year Plan.

the New Mexico Energy, Minerals and Natural Resources Department (MMD) oversee the assessment, abatement, and reclamation activities at these sites. The site owner/operators are required to investigate and abate radiological and metal contamination in groundwater under the abatement plans. The NMED noted in the pre-CERCLIS screens that, although reclamation and closure under the New Mexico Mining Act had been completed for some of these legacy mine sites, the aerial radiological survey conducted by the EPA of the ALSD measured elevated gamma radiation levels at these reclaimed sites. The NMED indicated that it may revisit the recommendations for no further action under CERCLA at these 15 sites should additional information become available that indicates a threat to human health or the environment.

New Mexico Energy, Minerals, and Natural Resources Department

From 2010-2014, the MMD, working with the NMED, developed integrated methods and protocols as guidance for site characterization and cleanup goals at existing and new sites being regulated under New Mexico's mine permitting and groundwater discharge permitting programs. These protocols were developed to resolve inconsistencies in cleanup goals established by the departments under their regulatory authorities. These protocols are defined in the draft "*Joint Guidance for the Cleanup and Reclamation of Existing Uranium Mining Operations in New Mexico*", dated March 2014, and the draft "*Guidance for Meeting Radiation Criteria Levels and Reclamation at New Uranium Mining Operations, Title 19, Chapter 10, Part 3 and Part 6, New Mexico Administrative Code*", dated April 2014.

From 1990-2003, the MMD safeguarded hazardous mine openings at 12 legacy uranium mines in the Poison Canyon area. The MMD is currently overseeing surface reclamation at nine (9) mine sites and developing site assessment and engineered reclamation designs for approximately 20 legacy uranium mines that are located primarily on Bureau of Land Management (BLM) administered lands in the Poison Canyon area. Reclamation activities will primarily address remediation of waste rock piles and physical hazards, which will assist in mitigating contaminant pathways.

To help identify and coordinate reclamation activities, the MMD has also developed a uranium mine inventory to compile information and reclamation status on all known uranium mines in New Mexico.

Bureau of Land Management

In 1985-87 approximately 40 legacy uranium mines on BLM property were inventoried in the checkerboard areas in the ALSD. All of these sites predate the BLM's surface management authority which was promulgated in 1981.

The BLM manages about 13 million acres of public land in New Mexico, which includes hundreds of dangerous abandoned hard rock mine features such as open shafts, adits, and pits; waste rock and tailings; and dilapidated buildings and structures. These dangerous mine features, especially those in high use areas and near cities and towns, present an elevated risk to the public.

The project objective is to improve the quality of public lands placed in the BLM's care by mitigating hazards present at abandoned mine sites, restoring watersheds for natural resource value when practical, and protecting health and safety. Addressing and remediating abandoned mine land impacts is becoming increasingly important as more and more people choose to live and recreate near public lands.

The BLM has been working with the MMD's Abandoned Mine Land Program for several years in characterizing and remediating abandoned mines throughout the state, and has recognized the MMD as a partner agency in this effort. The BLM will work with MMD through an Assistance Agreement and will pursue several million dollars of funding for the next several years. The results of a successful partnership will be the remediation of the most dangerous abandoned mine land features on the public land administered by the BLM in New Mexico, including, but not limited to, legacy uranium mines.

Two major legacy uranium mining areas that are a high priority are the Barbara J Mine complex and the Mesa Top Mine complex, located along Poison Canyon on BLM land near Grants. Radiation surveys were performed by the MMD in 2009. Site evaluations of the Barbara J Mine complex, including soil sampling and analysis, were completed in 2014. Physical hazards and elevated radon levels associated with open boreholes and shafts, as well as elevated radiation levels at the mine waste piles, make the remediation of these areas the highest priority in the effort to protect human health. The BLM completed a removal action design in 2014 to close the shafts and bore holes and cap highest radiation levels. The BLM reviewed a reclamation plan for the Rio Puerco Mine, including a proposed bond to meet financial assurance requirements, which was submitted by the operator in 2014. The BLM also completed an environmental assessment of the Spencer Mine. Erosion has resulted in the mine shaft being head cut by an arroyo and filled with sediment. The head frame has also fallen over. A reclamation plan is being developed by the MMD to control erosion at the Spencer Mine. Current plans are to re-route drainage around the site, backfill erosion features around the head frame, cover mine waste with three feet of soil and seal the vent shaft with polyurethane.

The state's Abandoned Mine Land Program has initiated characterization in the Poison Canyon area and estimates cost of four to five million dollars for engineering, administration and construction. The BLM, facilitated by the above-mentioned Assistance Agreement, will work with MMD in final prioritization of remediation and funding to address the entire Grants Mining District.

U.S. Forest Service

The U.S. Forest Service (USFS) developed and implemented an environmental cleanup plan for the San Mateo Mine under its CERCLA authority. The site is located on the Mount Taylor Ranger District of the Cibola National Forest. Elevated concentrations of uranium and Radium 226 were found present in the waste rock and leach pad at the site. The USFS prepared an Engineering Evaluation and Cost Analysis (EE/CA) report to identify and evaluate removal action alternatives and a risk assessment for threats to potential recreational visitors and the environment. Under a Unilateral Administrative Order for Removal Action from the USFS, the operator completed the site cleanup in 2013. The work consisted of regrading waste rock piles, excavation of surface soil over a 100-acre area and consolidation around the waste rock piles to form a 24-acre waste repository, construction of a 3.5-foot thick evapotranspiration soil and vegetative cover on the top of the repository, and fencing. Quarterly inspections and operation and maintenance (O&M) will be performed by the operator for a period of five years, after which the USFS will assume future O&M responsibilities. Groundwater was not investigated as part of the Removal Action performed at the San Mateo Mine. The USFS completed the draft EE/CA for the Cibola Uranium Mines in 2014. These mines include the Zia, Taffy, old La Jara and Vallejo Mine sites located on USFS lands.

U.S. Environmental Protection Agency

In 2010 and 2011 the EPA conducted Airborne Spectral Photometric Environmental Collection Technology (ASPECT) overflights of the ALSD to collect gamma radiological measurements. Results from the ASPECT aerial gamma surveys indicated elevated gamma radiation activity at many legacy uranium mine sites, with the largest gamma radiation anomalies located at mine sites in the Ambrosia Lake area and near the village of San Mateo that operated as wet mines with mine water discharges to ground surface.

After reviewing the pre-CERCLIS screens and the results from the ASPECT aerial gamma survey, the EPA concluded that an investigation was needed to determine if hazardous substances had been released to the environment from legacy uranium mine sites in the Grants Mining District. Several legacy mines were targeted for field sampling based on the size of the gamma radiation anomaly detected in the ASPECT aerial gamma survey. In 2012 and 2013, the EPA conducted Documented Release Sampling (DRS) at nine legacy uranium mines:

- Mary No. 1 Mine, Ambrosia Lake area;
- Dysart No. 2 Mine, Ambrosia Lake area;
- John Bully Mine, Ambrosia Lake area;
- Sandstone Mine, Ambrosia Lake area;
- Section 10 Mine, Ambrosia Lake area;
- Section 12 Mine, Ambrosia Lake area;
- Section 15 Mine, Ambrosia Lake area;
- Section 30 Mine, Ambrosia Lake area;
- Marquez Mine.

The DRS included the collection of surface gamma radiation measurements and surface soil samples for performing chemical/radiological analyses. The sampling objectives were to collect data that could be used to document a release of hazardous substances to the environment. The results of the DRS showed soil contamination attributable to the sites included Radium 226, molybdenum, selenium, uranium and other metals as well as gamma radiation. Based on these results, the EPA concluded that a release had occurred to soil at all nine legacy mine sites evaluated, including one site (Section 30 Mine) that had previously been reclaimed under the New Mexico mine permitting program.

Johnny M Uranium Mine

The Johnny M uranium mine site is a legacy uranium mine located within the Grants Mining District. It is located along New Mexico Route 605/San Mateo Road approximately four miles west of the village of San Mateo. The mine was developed and operated from 1972 through 1982 by Ranchers Exploration and Development Corporation. Hecla Limited acquired mining interests in the site through a merger with Ranchers in 1984. The mine consisted of an underground mining operation which utilized surface support facilities, including two sand fill storage areas, two discharge ponds, a ditch with a water discharge pipe routed to a nearby drainage that connected to San Mateo Creek, and a water supply well. As part of mining operations, mill tailings purchased from the Kerr-McGee uranium mill in the ALSD were slurried into the underground to stabilize the mine workings beginning in 1977. An estimated 286,000 tons of tailings material was slurried and pumped into the mine at depths of 1100 – 1300 feet. Two surface locations were used for temporary storage of the uranium tailings prior to its placement in the mine stopes. The use of

uranium mill tailings at the mine, including backfilling, was approved by the New Mexico Environmental Improvement Division, the predecessor to NMED.

Reclamation and closure activities were conducted after cessation of mining in 1982 under the direction and oversight of the New Mexico Environmental Improvement Division. The NRC became the licensing authority for the source material (tailings) and reclamation of the tailings storage and backfill areas in 1986 and issued Source Materials License SUA-1482 in 1988. The license was terminated in 1993 when the NRC determined that reclamation efforts were completed.

In 2010, New Mexico Environment Department personnel noticed elevated radiation levels at a residence located adjacent to the mine site when conducting sampling of a private water supply well. The EPA was requested to evaluate the site for possible removal action. The EPA tasked its contractor to conduct both a Phase I outdoor gamma radiation assessment on portions of the site and a Phase II indoor assessment for radon gas at the residence, stables and barns. Surface and subsurface soil samples were collected from areas with elevated gamma readings around the residence and horse stables area. The sampling results indicated possible releases to the sediment/soil in the residential and horse stable areas.

The EPA determined that conditions on the residential property posed an unacceptable health risk to the residents and initiated relocation in 2011 as a time-critical removal action. New Mexico Land, LLC purchased the property on February 2, 2012.

In 2012, the EPA entered into an Administrative Settlement Agreement and Consent Order with Hecla Limited and New Mexico Land, LLC for the performance of a removal action under CERCLA. The work performed under this consent order included site stabilization to manage runoff and run on, performance of a site assessment, and the preparation of a site investigation report and engineering evaluation/cost analysis (EE/CA). A groundwater investigation was not included as part of the consent order, nor was sampling of sediment in San Mateo Creek at the discharge point from the mine site drainage. Based on the site investigation report and EE/CA, there is an estimated 500,000 cubic yards of contaminated soil that will need to be addressed.

U.S. Geologic Survey

The USGS, working in partnership with the USFS, completed a hydro-geologic study to characterize aquifers within the upper San Mateo Creek Basin near Mt. Taylor in 2010-2011. The study focused on aquifer areas on USFS lands that are proposed for exploratory uranium drilling and possible mining. Most of the study area is within the upper San Mateo Creek basin but also includes small areas along the hydrologic divide of the San Mateo and Cañada Las Vacas Basins to the north and the San Mateo and Lobo Creeks to the south. Results of this study are published in *USGS Scientific Investigation Report 2012-5019: Geologic Framework, Regional Aquifer Properties (1940s-2009)*, and *Spring Creek, and Seep Properties (2009-2010) of the Upper San Mateo Creek Basin near Mount Taylor, New Mexico*.

The USGS, through its State Map Geologic-Mapping Program, has provided funding to the New Mexico Bureau of Geology and Mineral Resources for mapping six-7.5 minute quadrangles in the Grants Mining District, including the Ambrosia Lake, San Lucas Dam, and Cerro Pelón quadrangles for which mapping is in progress and the San Mateo, Lobo Springs, and Mt. Taylor quadrangles for which mapping was recently completed. In 2011, the New Mexico Bureau of Geology and Mineral Resources began geologic mapping of quadrangles on the east side of Mt. Taylor.

Other USGS activities not necessarily taking place in the Grants Mining District but are relevant include:

- Preparation of a bibliography of USGS publications on research conducted in the Grants Mining District inclusive of references and abstracts;
- Research to examine isotopic compositions, primarily of uranium and sulfur, in water in relation to a variety of solid phase sources;
- Preparation of “Uranium and the Environment” community education modules for Native American communities in the Grants Mining District to be developed in consultation with the New Mexico Environment Department, the EPA and possibly others.

The New Mexico Bureau of Geology and Mineral Resources and New Mexico Institute of Mining and Technology have had an active program in uranium resources, uranium geochemistry and remediation around New Mexico for many years. The studies have included a uranium resource assessment for the state, understanding the mobility of uranium in the environment and what influences migration of uranium in soil, understanding uranium bioavailability to plants and the potential application of phytoremediation to mitigate contamination in a semi-arid environment, site assessment studies at abandoned mine sites that include soil and plant surveys, and looking at traditional and non-traditional technologies for remediating mine and mill sites.

Objective 3: Assess, Cleanup, and Long-Term Management of Former Uranium Milling Sites

Background

In enacting the Uranium Mill Tailings Radiation Control Act of 1978, Congress had two general goals. The first was to provide a remedial action program to stabilize and control radioactive mill tailings at various inactive mill tailing sites. The second was to ensure adequate regulations for uranium production activities and cleanup of mill tailings at mill processing sites that were active and licensed by the NRC (or Agreement States). At the time, the NRC did not have direct regulatory control over uranium mill tailings because the tailings did not fall into any category of the NRC licensable material. Before 1978, the NRC was regulating tailings at active mill sites indirectly through licensing of source materials milling operations under the Atomic Energy Act of 1954, as a result of the enactment of the National Environmental Policy Act of 1969, to address environmental impacts of licensing actions.

Under provisions of Title I of the Uranium Mill Tailings Radiation Control Act, Congress addressed the problem of inactive, unregulated mill tailing piles. Title I specifies the inactive mill sites for remediation. Under Title I, the EPA establishes standards for cleanup and disposal of contaminated material; the DOE identifies and remediates the sites and vicinity properties to the EPA standards; the NRC evaluates and concurs with the DOE remediation plans and concurs when site remediation has been adequately completed. Upon completion of decommissioning, the DOE becomes the long-term site custodian under the NRC General License and is responsible for performing routine surveillance and maintenance activities.

Title II of the Uranium Mill Tailings Radiation Control Act addresses the issue of mill tailings produced at active mill operations sites licensed by the NRC or Agreement States. Title II amended the definition of byproduct material to include mill tailings and added specific authorities for the NRC to regulate this new category of byproduct material at licensed sites. Under Title II,

the EPA establishes standards for cleanup and disposal of byproduct material; the NRC or Agreement State reviews license applications, issues licenses, conducts inspections, and oversees the decommissioning activities in meeting EPA standards; the NRC, which incorporated the EPA standards in its regulations, reviews and concurs on the DOE Long-Term Surveillance Plans for conventional mills; the NRC or the Agreement State terminates the specific licenses for the mill operations sites and the NRC concurs with Agreement State license termination. Upon completion of decommissioning, the DOE becomes the long-term site custodian under the NRC General License.

Remediation criteria for uranium mills were first promulgated by the EPA in 1983, and amended in 1987. These criteria, which are found in 40 CFR Part 192, Health and Environmental Protection Standards for Uranium and Thorium Mill Tailings, are as follows:

Soil and buildings:

- Five picocuries per gram (pCi/g) averaged over the first 15 centimeters (cm) of soil below surface;
- 15 pCi/g averaged over 15 cm thick layers of soil more than 15 cm below surface;

Radon:

- 20 pCi/m²sec;

Groundwater:

- Background or maximum contaminant level, whichever is higher, or
- Alternate concentration limit.

The NRC's final regulations for mill tailings were promulgated in 1985 and amended in 1987 in 10 CFR Part 40, Appendix A, *Criteria Relating to the Operation of Uranium Mills and the Disposition of Tailings or Wastes Produced by the Extraction or Concentration of Source Material from Ores Processed Primarily for their Source Material Content*.

Four legacy uranium mill sites are located within the ALSD. The Ambrosia Lake-Philips Mill site, a Title I site, and the Anaconda Bluewater Mill site, a Title II site that was reclaimed and transferred to the DOE in 1997, are in the custody of the DOE for long-term surveillance, maintenance and groundwater monitoring under the NRC general license provisions. The Homestake Mining Company Mill Superfund site and Rio Algom-Ambrosia Lake Mill site are both Title II sites under the jurisdiction of the NRC for reclamation. The Homestake Mining Company Mill Superfund site is also under the jurisdiction of the EPA for CERCLA response actions. Located in the Laguna mining sub-district is the L-Bar Mill site, a Title II site that was reclaimed and transferred to the DOE in 2004 for long-term surveillance, maintenance and groundwater monitoring. The Bokum Mill is located within the Marquez mining sub-district; according to the NRC records, the source material license was terminated in 1988 following multiple inspections, which confirmed that no uranium ore was ever produced or processed at the site.

The United Nuclear Corporation Mill – Northeast Church Rock Superfund site is located outside of the Grants Mining District but presents similar environmental issues and concerns related to legacy uranium milling activities in northwestern New Mexico.

Previous and Ongoing Regulatory Actions

Anaconda Bluewater Mill Site (U.S. Department of Energy)

The 3,300-acre former Anaconda Bluewater Mill site is located in Cibola County in west central New Mexico. The Anaconda Copper Company constructed the original carbonate-leach mill at the site in 1953 to process uranium ore. The mill had a production capacity of 300 tons of ore per day. Mill effluents were stored in unlined evaporation ponds. Water budget calculations and groundwater monitoring indicated the occurrence of substantial leakage from these ponds. In 1959, the Anaconda Copper Company drilled a deep well for injection disposal of mill effluents. This well was operated between 1960 and 1977. By 1965, an estimated 500 million gallons of effluent had been injected. Water pressure monitoring and hydraulic head/flow calculations indicated that injected effluents may have leaked to overlying formations.

Milling operations at the site ended in 1982. It is estimated that several billion gallons of tailing fluid seeped through the bottom of the main tailings impoundment and into the underlying aquifers prior to the construction of the disposal cell cover in 1995. The tailing seepage contaminated the ancestral Rio San Jose alluvial system and the bedrock San Andres Limestone/Glorieta Sandstone aquifer with molybdenum, selenium, and uranium. Several years of active remediation by pumping contaminated groundwater from the aquifers produced no significant reduction in contaminant concentrations. In accordance with NRC regulations at 10 CFR Part 40, Appendix A, and EPA standards at 40 CFR Part 192, when background and drinking water limits are not practically achievable, alternate concentrations may be considered. Based on the criteria evaluated, the NRC approved site-specific alternate concentration limits for contaminants of concern in 1996, and transferred the site to the DOE for long-term surveillance, maintenance and groundwater monitoring in 1997.

Surface remediation consisted of consolidating and encapsulating all contaminated material on site in an engineered disposal cell, which covers about 320 acres and contains an estimated 23 million tons (16 million cubic yards) of tailing and other contaminated material having a total activity of about 11,200 curies of Radium-226.

The DOE manages the tailing disposal cell according to a site-specific Long-Term Surveillance Plan concurred on by the NRC to ensure that the disposal cell systems continue to prevent release of contaminants to the environment. Under provisions of this plan, the DOE conducts annual inspection of the site to evaluate the condition of surface features, perform site maintenance as necessary, and monitor groundwater to verify the integrity of the tailing disposal cells. The NRC performs oversight of these actions under UMTRCA Title II. The DOE compliance strategy includes annual groundwater monitoring. Groundwater samples are analyzed annually for polychlorinated biphenyls and every three years for molybdenum, selenium, and uranium.

In 2008, the NMED conducted a site investigation of the Bluewater Disposal Site, and sampled 33 San Andres aquifer wells in the area for an expanded list of metals and radionuclides. NMED also reviewed well construction diagrams and sampling protocol for representative sampling and determined that the sampling results for uranium were suspect and not representative of the true ground water quality of the San Andres Aquifer beneath the site. DOE conducted their own analysis of the well construction, sampling protocol, and laboratory results and concluded the integrity of two monitoring wells to yield a representative sample was compromised and that there were also gaps in the monitoring network.

During 2011-2012, DOE installed and sampled six new San Andres aquifer wells and four new alluvial wells at the site in order to gain a better understanding of the hydrogeology-geochemistry

of ground water, and to respond to questions raised by the NRC in mid-2012. DOE determined that contamination in the alluvial aquifer was exceeding the uranium standard (0.44 mg/L) at the Point of Exposure well (boundary), and that contaminated San Andres ground water extends beyond the site boundaries. NRC directed the DOE to conduct further analysis of the site including an assessment of exposure and human-health risk to off-site San Andres aquifer well users.

In 2014, DOE conducted a study to develop a revised ground water conceptual model for the site, and to determine if there is potential exposure to down gradient users of ground water from mill-related contamination. The DOE completed a status report on the flow and contaminant transport from the Anaconda Bluewater Disposal Site in November 2014, and concluded that no drinking water wells are within the contaminant plume and that the Milan and Grants municipal wells will not be affected.

Ambrosia Lake – Phillips Mill Site (U.S. Department of Energy)

The Ambrosia Lake – Phillips Mill is a former uranium ore processing facility in McKinley County, approximately 25 miles north of Grants, New Mexico, near the Rio Algom-Ambrosia Lake Mill site. The site is within the ALSD, near the center of the Grants Mining District. Numerous abandoned underground mines are located in close proximity to the site. The mill processed more than three million tons of uranium ore between 1958 and 1963 to provide uranium for the U.S. Government national defense programs. All mill operations ceased in 1982, leaving radioactive mill tailings on approximately 111 acres. Wind and water erosion spread some of the tailings across a 230-acre area. The DOE remediated this site and contaminated near-vicinity properties between 1987 and 1995 under Title I of the Uranium Mill Tailings Radiation Control Act. Surface remediation consisted of consolidating and encapsulating all contaminated material on site in an engineered disposal cell. An engineered disposal cell, which occupies 91 acres of the 290-acre site, encapsulates all site-derived contaminated material. Groundwater remediation of the site was not conducted due to the determination by the DOE that the groundwater in the uppermost aquifer underlying the site is of limited use based on aquifer yield.

The DOE manages the disposal site according to a site-specific Long-Term Surveillance Plan concurred on by the NRC to ensure that the disposal cell systems continue to prevent release of contaminants to the environment. Under provisions of this plan, the DOE conducts annual inspections of the site to evaluate the condition of surface features, performs site maintenance as necessary, and samples two monitoring wells every three years. The NRC performs oversight of these actions under UMTRCA Title I.

The NMED reviewed information regarding the Ambrosia Lake-Phillips Mill site in 2009. The NMED identified possible inadequacies in the site hydrologic assessment and remediation, and also documented that mill tailing had been used to backfill some area mines.

Homestake Mining Company Mill Superfund Site (U.S. Nuclear Regulatory Commission and U.S. Environmental Protection Agency)

The Homestake Mining Company Mill Superfund site is located in Cibola County, New Mexico, approximately 5.5 miles north of the village of Milan, at the intersection of Highway 605 and County Road 63. An alkaline leach-caustic precipitation process mill was operated at the site from 1958 until 1990. Tailings entrained in solution from the milling process was placed into lagoons on top of two unlined disposal piles, a large tailings pile and a small tailings pile, which together cover an area of 170 acres. Approximately 1.2 million tons of tailings was disposed of in the small tailing pile and 21 million tons of tailings were disposed of in the large tailings pile.

From 1958 through 1974, the site was regulated by the Atomic Energy Commission under License Number SUA-708. In 1974, regulatory authority was granted to the State of New Mexico as an Agreement State.

Contamination of groundwater in the alluvial aquifer was first noted by the EPA in 1975. Based on these findings, United Nuclear-Homestake Partners (the owner of the site at that time) initiated groundwater abatement actions under the direction of the New Mexico Environmental Improvement Division (predecessor to the NMED) in 1977.

Contamination associated with the tailing material and milling operations have resulted in the creation of three operable units (OUs) at the site under CERCLA. The first operable unit, OU1, is the restoration of groundwater that is contaminated by tailing seepage. The second operable unit, OU2, concerns the long-term stabilization of the tailings, surface reclamation, decommissioning and closure of the mill. The third operable unit, OU3, addresses indoor and outdoor radon concentrations in residential areas adjacent to the site.

In 1986, regulatory authority over uranium milling and closure operations was transferred to the NRC and source materials license SUA-1471 was issued, replacing SUA-708. Homestake Mining Company conducted a surface soil cleanup to remove windblown tailing contamination in the vicinity of the large tailings pile beginning in 1988. Soil exceeding 5 pCi/g Radium-226 above background in the top 15 cm of soil was excavated and disposed of at the tailings facility. After a temporary shutdown of this work to complete mill decommissioning, the remainder of the windblown contamination was cleaned up in 1993. The mill was decommissioned and demolished between 1993 and 1995 and debris was buried at the former mill site.

Tailing seepage has contaminated four aquifers at the site: the shallow alluvium and three separate bedrock aquifers of the underlying Chinle Formation which sub crop with the alluvium. Homestake Mining Company currently conducts corrective action under the direction and oversight of the NRC to mitigate groundwater contamination. The corrective action consists of a groundwater extraction and injection system, tailing flushing and dewatering systems, a reverse osmosis water treatment system, a pilot zeolite groundwater system, two lined collection ponds, three lined evaporation ponds and associated equipment and structures. Homestake Mining Company has also disposed of excess contaminated groundwater collected by the extraction system at established Land Treatment Areas through irrigation. Decommissioning activities and groundwater corrective action activities are projected to be completed by 2022.

The NMED has regulatory authority at the site through issuance of groundwater discharge permit DP-200, which regulates several aspects of the ongoing groundwater remediation and related reverse osmosis water treatment system.

In 2008, the Agency for Toxic Substances and Disease Registry prepared a public health assessment report for the Homestake Mining Company Mill Superfund site. In the report the agency concluded that the lack of consistent water quality monitoring data, the uncertainty in the degree to which residents used groundwater from their private wells, including for irrigation and livestock watering purposes, and the lack of vegetable or soil sample results from gardens made past exposures an indeterminate health hazard. However, due to contaminant levels in groundwater being above drinking water standards and the potential for human exposure through use of this groundwater, the Agency for Toxic Substances and Disease Registry categorized the site as a public health hazard.

An updated revised groundwater corrective action program (CAP) was submitted to the NRC by the Homestake Mining Company in 2012. The primary purposes of updating the CAP was to: 1) document the status of the current restoration effort; 2) describe the adaptations necessary for source control and plume remediation; 3) to address the Request for Additional Information from the NRC after the review of the 2006 draft CAP revision; and 4) to address specific comments from the EPA and the NMED to assure that completion of the CAP will satisfy NMED requirements, and EPA criteria in order to be able to delete the site from the National Priorities List (NPL).

In 2013 Homestake Mining Company submitted an Updated Decommissioning and Reclamation Plan (DRP). This document supplements the Grants Reclamation Project site information as provided in the CAP update. This DRP updates the previous reclamation plan submitted by Homestake Mining Company to the NRC in October 1993, and provides supporting documentation to amend current license conditions for the completion of final groundwater restoration activities and remaining site decommissioning and reclamation activities. The updated DRP is currently under review by NRC. The NRC expects to issue a response to the document with a request for information and a response to the public comments in 2015. The NRC continues to review annual and semi-annual reports and conduct inspections of the site and site activities.

In 2015 NRC responded to Homestake Mining Company's CAP submittal with a request for additional information and responded to the public comments received on the CAP. NRC expects a response from Homestake Mining Company detailing how they responded to each request for additional information, and a revised CAP document based on those responses. If the NRC judges that the document can be approved, or approved with conditions, the next step would be to prepare an environmental assessment per our National Environmental Policy Act regulations in 10 CFR Part 51.

As directed by the EPA, the Homestake Mining Company submitted a remedial investigation and feasibility study (RI/FS) equivalency package containing historic records and information on site activities and a draft RI report to the EPA in 2014. The RI/FS equivalency package and RI Report are intended to support a determination by the agency that prior site activities under the NRC Source Materials License SUA-1471 are equivalent to an RI/FS and CERCLA-quality cleanup that would be conducted in accordance with CERCLA and the NCP. Such equivalency, including the public participation process in remedy selection and decision-making, would eventually be necessary to support NPL delisting of this site by the EPA.

Ambrosia Lake – Rio Algom (U.S. Nuclear Regulatory Commission)

The Ambrosia Lake – Rio Algom Mill site is located approximately 25 miles north of Grants, New Mexico, near the Ambrosia Lake – Philips Mill site. The tailing impoundment contains 33 million tons of uranium mill tailings and covers an area of approximately 370 acres. The site, which began underground mining operations in 1957, was the largest uranium ore processing facility in North America. It produced over 130 million pounds of uranium concentrate and generated 33 million tons of tailings. The mill was placed on standby in 1985; however, limited production continued through the use of old stope leaching through 1999. Between 1999 and 2002, minor amounts of uranium were produced as part of a groundwater remediation program.

Groundwater reclamation was completed in 2001 in accordance with the NRC license. Surface reclamation is nearing completion. The site status changed from standby to reclamation in August 2003 to reflect the licensee's intent to begin full demolition and reclamation of the site leading to termination of the specific license. The mill was demolished and disposed of in the tailing

impoundment in late 2003. The NRC issued a license amendment for alternate concentration limits at the site in February 2006. Groundwater corrective actions continue under an abatement plans and discharge permit DP-169 issued by the NMED, and Rio Algom is finalizing the site tailing reclamation.

Reclamation of the mill site is largely complete. A radon barrier was constructed over Tailings Impoundment 1 in 1999 and the mill was decommissioned in 2005. Additional reclamation tasks were completed in subsequent years, including the construction of a 1000-year diversion channel for the Arroyo Del Puerto. In 2014 and 2015, all remaining structures at the mill were demolished and consolidated remaining waste material into Tailings Impoundment 2. Completion of a radon barrier over Tailings Impoundment 2 is scheduled to be completed in the first half of 2016.

Groundwater monitoring occurs at the site pursuant to the NRC license. The NRC approved Alternative Concentration Limits (ACLs) for groundwater at the site through issuance of an Environmental Assessment and Finding of No Significant Impact in January 2006. Investigations are currently underway to demonstrate equivalency with NMED's abatement process. Rio Algom has agreed to submit a petition to the New Mexico Water Quality Control Commission for alternate abatement standards.

Once all decommissioning and reclamation tasks are complete, the specific license will be terminated with the NRC and the site ownership will be transferred to the DOE for perpetual care and maintenance in accordance with the Uranium Mill Tailings Radiation Control Act (UMTRCA). License termination and handover to DOE is currently estimated to occur in 2020.

L-Bar Mill (U.S. Department of Energy)

The former L-Bar Uranium Mill site is located in Cibola County, approximately 47 miles west of Albuquerque, New Mexico, and 10 miles north of Laguna Pueblo. The site is located on part of the former L-Bar Ranch and is about four miles east-southeast of the village of Seboyeta. The site was previously owned and operated by SOHIO Western Mining Company. Mining and milling at L-Bar began in 1977 and continued until 1981, when the nearby mine closed due to unfavorable uranium industry economic conditions. About 2.1 million tons of uranium ore were processed at the mill. SOHIO Western Mining Company completed site surface reclamation in 2000.

The L-Bar Mill site currently comprises an area of 740 acres and includes a 100-acre disposal cell containing approximately 700,000 cubic yards of tailings. Groundwater withdrawal essentially dewatered the first Tres Hermanos Aquifer underlying the site, decreasing well yields to the point that recovery of contaminants was no longer effective. The DOE's compliance strategy at the site is application of the NRC approved alternate concentration limits and the New Mexico Water Quality Control Commission-approved alternate abatement standards for the contaminants of concern. The DOE will conduct groundwater monitoring annually for three years; if monitoring results indicate that seepage from the disposal cell is under control, the sampling frequency will be reduced to once every three years thereafter. Groundwater monitoring will continue as long as any contaminant of concern or total dissolved solids concentrations in any point-of-compliance well exceeds a state groundwater protection standard.

United Nuclear Corporation Mill – Northeast Church Rock Superfund Site (U.S. Nuclear Regulatory Commission and U.S. Environmental Protection Agency)

The United Nuclear Corporation Mill – Northeast Church Rock Superfund site is located 17 miles northeast of Gallup, New Mexico and on the southern border of the Navajo Indian Reservation. United Nuclear Corporation was granted a radioactive materials license by the State of New

Mexico in 1977 and operated the site as a uranium mill facility from 1977 to 1982. The site includes a former ore processing mill and an unlined tailing disposal site which cover about 25 and 100 acres respectively. The tailing disposal site is subdivided by cross-dikes into three cells identified as the South cell, Central cell and North cell. In 1979, the dam on the South cell was breached, releasing approximately 93 million gallons of tailing and pond water into the Rio Puerco. The dam was repaired shortly after its failure and the cleanup of the resultant spill was conducted according to criteria imposed by state and federal agencies at the time. Tailing liquids seeped downward from the leaking disposal cells to contaminate the shallow alluvium (referred to as the Southwest Alluvium) and two aquifer zones (Zone 1 and 3) of the Upper Gallup Sandstone Formation with radionuclides and chemicals. The EPA placed the site on the NPL of Superfund sites in 1983 because of the groundwater contamination from tailing seepage and other releases to surface water and air.

In 1986, the NRC assumed responsibility for the licensing and regulating of uranium mills within the State of New Mexico at the request of the Governor. The tailing disposal cells have been capped with an interim radon barrier cover as part of the reclamation activities performed under the direction of the NRC.

The EPA issued a Groundwater Operable Unit Record of Decision (ROD) in 1988. The selected remedy consisted of extraction of groundwater from the Southwest Alluvium and Zone 1 and 3 and treatment by evaporation. United Nuclear Corporation constructed the groundwater remedy in 1989, and continues to operate a portion of the remedy in accordance with the 1988 Record of Decision.

For Groundwater Operable Unit 01, the United Nuclear Corporation is currently extracting seepage-impacted groundwater from Zone 3 to an evaporation pond on-site under a CERCLA Unilateral Administrative Order issued by the EPA. The extraction systems for Zone 1 and the Southwest Alluvium are shut off. The Zone 1 extraction system was shut down in 1999 because it had reached its limit of effectiveness in achieving the cleanup levels because of significant declines in pumping rates over time due to insufficient natural recharge of the aquifer. The extraction system was shut off for the Southwest Alluvium because there was little progress in achieving some site cleanup levels over time.

Due to the dysfunction of the remedial system, the EPA directed United Nuclear Corporation to complete a Site Wide Supplemental Feasibility Study. While conducting this study, United Nuclear Corporation also performed interim measures to improve the existing extraction system with little or no success. After 25 years of active site remediation, the cleanup levels are still unattained.

In 2013, the EPA issued a ROD for the Surface Soil Operable Unit. The selected remedy includes the transportation of approximately one million cubic yards of contaminated soil and mine waste from the adjacent Northeast Church Rock uranium mine site to the United Nuclear Corporation Mill Superfund site for consolidation and disposal within the tailing disposal site for an estimated cost of \$41.5 million.

Additionally, the EPA has completed negotiations on a CERCLA Administrative Order on Consent with United Nuclear Corporation for implementing the remedy selected in the 2013 Record of Decision. United Nuclear Corporation has also prepared and submitted required pre-draft design reports and other study reports in 2014 for the agencies to review.

Objective 4: Assess and Cleanup of Contaminated Structures and Properties

Background

Some structures within the Grants Mining District may be constructed or remodeled with radiological contaminated materials from legacy uranium sites or located on legacy uranium sites and may pose risks to human health. Additionally, some residential or commercial properties within the District may contain radiological contaminated materials from legacy uranium sites that were transported to the properties by former uranium mine workers and may pose risks to human health.

Previous and Ongoing Regulatory Actions

U.S. Environmental Protection Agency

The EPA initiated removal site assessments at potentially-contaminated residential structures in the Ambrosia Lake and Laguna mining sub-districts of the Grants Mining District in 2009. The removal assessment was conducted in two general phases: 1) aerial radiological survey conducted by the EPA owned aircraft equipped with ASPECT Gamma Emergency Mapper, and 2) on-the-ground residential radiological survey using a peer reviewed assessment protocol developed specifically for this assessment.

Five general areas of interest were originally targeted for aerial radiological assessment by the ASPECT in the Ambrosia Lake mining sub-district: 1) the greater Grants area (includes Milan, Toltec, Bluewater, and San Rafael), 2) the village of San Mateo, 3) the area surrounding the intersection of State Highway 605 and State Highway 509, 4) the Mormon Farms area (south of the Homestake Mining Company Mill Superfund site), and 5) the Lobo Canyon sub-divisions. Within the Laguna mining sub-district, two areas were targeted for aerial radiological assessment: 1) the six main villages of the Laguna Pueblo (Paguete, Encinal, Seama, Paraje, Laguna and Mesita) and 2) the three villages of the Cebolleta Land Grant (Bibo, Moquino, and Seboyeta). The Laguna mining sub-district area was addressed as the Oak Canyon site.

The aerial radiological assessment was completed in October 2009 and the final report completed in January 2010. Copies of the final report were distributed to the other Agencies and a copy was made available for public review at the public library in Grants, New Mexico. Results from the aerial radiological assessment allowed the EPA to prioritize its resources for those areas of greatest probability for excessive radiological contamination within the five original areas of interest. Areas of highest priority were the village of San Mateo in the ALSD and all of the Oak Canyon site (Laguna mining sub-district).

In December 2009, the EPA began public outreach and seeking voluntary access to conduct the on-ground removal assessments. In January 2010, the on-ground radiological surveys and residential radon sampling commenced, beginning in the three villages of the Cebolleta Land Grant at the Oak Canyon site. From 2010 through 2014, the EPA's Removal Program assessed over 900 structures and properties for gamma and elemental uranium contamination. All of the villages of the Pueblos of Laguna and Acoma, the villages of Bluewater, San Mateo, and the Cebolleta Land Grant, and the subdivisions and Mormon Farms area south of the Homestake Mining Company Mill Superfund site were assessed. Of those checked, 128 of the assessed properties had soil radiation above action levels and were cleaned up. One structure was demolished and another was replaced with a modular house. One resident living in close proximity to a legacy uranium mine was relocated. The following cleanup activities were performed over this time period:

- *Bear Canyon Site-Cebolleta Land Grant, Villages of Bibo and Seboyeta*
 - Soil removals were completed at 12 residential properties with soil transported to Clive, Utah, for disposal.
 - Radon Abatement systems were installed in five homes.
- *Cross Roads Area Site (Near State Highways 605 and 509)*
 - Soil removals were completed at eight residential properties and soil will be transported to Deer Trail, Colorado.
 - Radon abatement systems were installed in two homes.
- *Hogan Mine Site*
 - Paving rocks were removed at one residence and transported to Clive, Utah, for disposal.
- *Johnny M Mine, near Village of San Mateo*
 - One resident was relocated.
- *Middle Reservoir Road Site, Village of Paguete*
 - A structure was replaced with a modular house.
- *Mormon Farms Area South of Homestake Mining Company Mill Superfund Site*
 - Constructed waste staging area for removal actions planned for 19 properties.
 - Soil removals were completed at 19 residential properties with soil transported to waste staging area. The soil has been transported to Deer Trail, Colorado for disposal.
- *Mount Taylor – San Mateo Radiation Site, Village of San Mateo*
 - Soil removals were completed at 12 residential properties with soil transported to Clive, Utah for disposal.
 - Radon abatement systems were installed in seven homes.
- *Oak Canyon Site-Village of Paguete*
 - Soil removals were completed at nine residential properties with soil transported to Clive, Utah for disposal.
 - Radon abatement systems were installed in 23 homes.
- *Pueblo of Acoma Villages-Canyon Largo Site*
 - Soil removals were completed on two properties with soil transported to Deer Trail, Colorado for disposal.
 - One radon abatement system was installed.
- *Rio San Jose Radiation Site, Villages of Mesita, Paraje, Laguna, and Seama*

- Soil removals were completed at 14 residential properties located in four villages on Pueblo of Laguna land with the soil transported to Clive, Utah for disposal. Radon abatement system was installed in one home.
- *Subdivisions South of Homestake Mining Company Mill Superfund Site*
 - Radon abatement systems were installed in eight homes.
- *Sun Clan Road Site, Village of New Laguna*
 - One structure was demolished. The owner was compensated for their home.
- *Bluewater Radiological Site, Village of Bluewater*
 - Soil removals were completed at 26 residential properties with soil transported to Deer Trail, Colorado for disposal. Radon abatement systems were installed in six homes.

Objective 5: Laguna Pueblo/Jackpile Mine

Background

The Jackpile-Paguate uranium mine site is located within the Pueblo of Laguna, near the village of Paguate, and approximately 40 miles west of Albuquerque, New Mexico. The mine was started by Anaconda Copper Company in 1953 and operations ceased in 1982 by the Atlantic Richfield Company (ARCO). Open pit and underground mining activities were conducted under lease agreements, with mining leases covering approximately 7,868 acres. Approximately 2,656 acres were disturbed by mining. The mining operation included the excavation of three large open pits: the Jackpile pit and the North and South Paguate pits. The mine also included 32 waste rock dumps, 23 protore (sub-grade ore) stockpiles, four topsoil stockpiles, and 66 acres of buildings and roads. Mine water was collected in sumps and pumped to ponds in the open pit. Uranium ore was stockpiled waiting for rail shipment to the Anaconda Bluewater Mill.

Previous and Ongoing Regulatory Actions

As part of the agreement made between Anaconda/ARCO and the Pueblo of Laguna, once operations at the mine ceased, ARCO was to pay for reclamation. In 1986, the BLM and Bureau of Indian Affairs completed an Environmental Impact Statement and issued a ROD. In 1989, the Pueblo of Laguna was paid approximately \$44 million by ARCO to conduct the reclamation work themselves. The Laguna Construction Company was created by the Pueblo of Laguna to do the reclamation. Reclamation was completed in 1994 and included backfilling the open pit areas using protore and waste rock dump material; sloping, regrading and covering remaining waste rock dumps; completing arroyo drainage improvements and erosion controls; decontaminating and removing structures; plugging and bulkheading underground ventilation raises and decline portals; and revegetating disturbed areas. Over 100 million tons of backfill, comprised mostly of ore-associated waste with some overburden, was returned to the pits.

The Pueblo of Laguna conducted a ROD compliance assessment for the mine site in 2007 to determine if the post-reclamation had met the requirements of the Environmental Impact Statement and ROD. It was determined that reclamation was not complete. Non-compliant issues included elevated gamma radiation and outdoor radon-222. At about this time, the Pueblo of Laguna began sampling surface water at various locations for analysis of uranium. Elevated levels of uranium were detected in the surface waters of the Rio Paguate and near Mesita Dam.

The levels of uranium could have an impact on Traditional/Cultural and Ceremonial uses of surface water bodies below the convergence of the Rio Paguete and Rio Moquino.

The Rio Moquino and Rio Paguete bisect the site and are in direct contact with the sources of contamination on site. Groundwater in the Jackpile Sandstone Aquifer interchanges with surface water from the Rio Moquino and Rio Paguete through the alluvium and deposits along the perennial river channels.

The EPA's first formal consultation was held with the Pueblo Governor and council members on October 13, 2009. A Memorandum of Understanding was signed by the Pueblo of Laguna and the EPA on June 22, 2010 to facilitate consultation, coordination and cooperation in performing removal and site assessment phases of activities for the site in accordance with CERCLA and the NCP.

The EPA conducted a preliminary site assessment in April 2010 and a site investigation in June 2010. Soil, sediment and surface water samples were collected in proximity to open pits, waste dumps and protore stockpiles around the site and analyzed. An expanded site investigation was performed by the EPA in April 2011. In 2013, the EPA placed the site on the NPL of Superfund sites. A Special Notice Letter was sent to ARCO in 2014 inviting ARCO to enter into settlement negotiations with the EPA for performing a remedial investigation/feasibility study at the Jackpile-Paguete Mine site in accordance with CERCLA and the NCP. ARCO decline to negotiate.

The EPA is the lead regulatory agency for the site and has the authority to conduct response actions at the Jackpile-Paguete Mine Superfund site under CERCLA.

The Pueblo of Laguna Environmental and Natural Resources Department has been given the authority by the Pueblo of Laguna Government to monitor and protect the environmental quality of the air, land, and water within the jurisdictional boundaries of the Pueblo of Laguna for the benefit of Pueblo member's health today and for future generations. The Pueblo of Laguna Environmental and Natural Resources Department programs are implemented in accordance with Pueblo of Laguna laws, codes, regulations and policies. The Pueblo of Laguna Codes contain codes for the Environment (Title XI), including Water Quality Standards (Chapter 2 of Title XI). Consistent with Title XI, Chapter 2, the Pueblo of Laguna will collaborate with federal and state agencies to prevent, reduce, and eliminate water pollution in coordination with programs managing water resources.

The EPA is continuing to consult and coordinate with the Pueblo of Laguna on all ongoing site-related activities. A remedial investigation/feasibility study is necessary to support the EPA's future decision-making on the appropriate CERCLA response actions to protect human health and the environment.

Objective 6: Public Health Surveillance

Background

Historical releases to ground and surface water, soil and air have been documented from legacy uranium sites throughout the Grants Mining District, and may be continuing into the present from on-site wastes. Area residents have requested health assessments associated with environmental impacts from historical known and possible legacy uranium activities and wastes in the San Mateo Creek Basin and throughout the Laguna sub-district.

Previous and Ongoing Regulatory Actions

The New Mexico Department of Health's Environmental Health Epidemiology Bureau has a long history of investigating New Mexicans' exposure to uranium.

From 2004-2008, New Mexico was a member of the six-state Rocky Mountain Biomonitoring Consortium (RMBC), which studied exposure to arsenic and other metals, including uranium. Biomonitoring is the assessment of human exposure to chemicals by measuring the presence of those chemicals (or their break-down products) in urine, blood, hair, saliva, or other biological samples. There are many reasons why biomonitoring is useful, but one reason is that the test result for a given chemical can be compared to average levels of this same chemical found in the general population (i.e. the US population). This can indicate if an individual or group has a higher or lower exposure to the chemical than the general population. The RMBC recruited volunteers so that baseline levels of chemicals could be determined for the participating New Mexico residents statewide. The New Mexico study focus was initially in areas with a known or suspected arsenic presence in drinking water. However, the results also indicated that urine uranium concentrations among volunteers were higher than the average uranium concentrations measured among the US population (National Health and Nutrition Examination Survey, 2005-2006). Specifically, the average volunteer in New Mexico had 0.03 micrograms per liter of uranium in their urine, whereas in the NHANES study, which consisted of a sample representative of the general US population, the average level was 0.005 micrograms per liter. This suggested that New Mexicans might have more exposure to uranium than the typical American.²

² Grants Mineral Belt Uranium Biomonitoring Project Summary, March 2011.

Message

From: Lattin, Daniel [dlattin@barrick.com]
Sent: 5/14/2019 11:36:28 PM
To: Purcell, Mark [purcell.mark@epa.gov]; Kurt Vollbrecht (kurt.vollbrecht@state.nm.us) [kurt.vollbrecht@state.nm.us]
CC: Malone, Patrick [pmalone@barrick.com]; Kevin Murray (krmurray@hollandhart.com) [krmurray@hollandhart.com]; Bingham, Brad [bbingham@barrick.com]; Arguello, Adam [aarguello@barrick.com]; McCarthy, Michael [mmccarthy@barrick.com]; Pierce, David [dpierce@barrick.com]; Burton, Clark [CBurton@barrick.com]; Ellie Rudolf [EARudolf@hollandhart.com]; Ulrich, Shannon [Shannon.Ulrich@arcadis.com]; Schlenker, Emily [Emily.Schlenker@arcadis.com]
Subject: GRP BG - Final 2019 Background Study Work Plan
Attachments: 20190513 GRP BG - Final 2019 Background Study Work Plan.pdf

Mark/Kurt,

As indicated during the May 7, 2019 call with EPA and NMED, Homestake is providing the attached Final 2019 Grants Reclamation Project Background Investigation Work Plan for your information. The following items have been updated from the February 13, 2019 Draft:

1. Addition of 2 additional boreholes (BK3 and BK4 as requested by EPA and NMED); current locations for all of the boreholes have been updated on Figure 4 of the Workplan and Figure 2 of the SAP.
2. Analytical plan updated to reflect requests from EPA and NMED, and to reflect the additional borehole (BK3; soil samples will be obtained from this location but not from BK4). The plan was also updated to include the modification to the sequential selection extraction (SSE) of soil to replace step 2 (exchangeable (MgCl₂)) with adsorbed (bicarbonate/carbonate extraction); justification for this change is included in the text. Finally, the analytical plan discussion of heavy liquid separation was removed because upon further discussion with the lab, this step is too complex, will introduce too many chemical artefacts to be able to get reliable data on uranium, and may not be successful. The sample numbers have all been modified to reflect current effort/scope.
3. QAPP has been signed and updated with current date.
4. The word "draft" has been removed from all parts of the document.

If you have any questions or comments, please don't hesitate to contact me directly.

Thank you,

BARRICK

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Daniel Lattin, P.E.
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Barrick Gold of North America, Inc.

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Homestake Mining Company of California
560 Anaconda Road, Route 605 North
Milan, New Mexico 87021

May 13, 2019

Mr. Mark Purcell
Superfund Division (6SF)
U.S. Environmental Protection Agency - Region 6
1445 Ross Avenue, Suite 1200
Dallas, TX 75202

Re: Grants Reclamation Project
2019 Background Investigation Work Plan Final

Dear Mark,

As indicated during the May 7, 2019 call with EPA and NMED, Homestake is providing the Final 2019 Grants Reclamation Project Background Investigation Work Plan for your information.

If you have questions or comments, please contact me at (775) 397-7215 or dlattin@barrick.com.

Respectfully,

Daniel Lattin, P.E.
Project Evaluation Manager
Homestake Mining Company of California



Homestake Mining Company of California

WORK PLAN: 2019 BACKGROUND INVESTIGATION

Grants Reclamation Project Grants, New Mexico

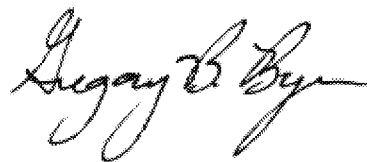
May 13, 2019



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WORK PLAN: 2019 BACKGROUND INVESTIGATION

Grants Reclamation Project Grants,
New Mexico

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Date:
May 13, 2019

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WORK PLAN: 2019 BACKGROUND INVESTIGATION

Figure 2	Site Layout
Figure 3	Conceptual Site Model Diagram
Figure 4	Proposed Geophysical Assessments and Borehole Locations

EXHIBITS

Exhibit 1	Example electrical resistivity tomography results
Exhibit 2	Thorium/potassium ratio plot for mineral identification using spectral gamma ray data

APPENDICES

Appendix A	Sampling and Analysis Plan
Appendix B	Proposed Well Construction Diagrams

ACRONYMS AND ABBREVIATIONS

%	percent
Arcadis	Arcadis U.S., Inc.
ASTM	ASTM International
bgs	below ground surface
CAP	Corrective Action Program
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
COC	constituent of concern
CSM	conceptual site model
EC	electrical conductivity
ERT	Electrical Resistivity Tomography
FRA	formal risk assessment
GPS	global positioning system
GRP	Grants Reclamation Project
GWPS	ground water protection standards
HASP	Site-Specific Health and Safety Plan
HMC	Homestake Mining Company of California
JSA	Job Safety Analysis

WORK PLAN: 2019 BACKGROUND INVESTIGATION

K	potassium
⁴⁰ K	potassium-40
LTP	large tailing pile
MeV	million electron volts
mg/L	milligram per liter
NGR	natural gamma ray
NMED	New Mexico Environment Department
NPL	National Priorities List
NRC	Nuclear Regulatory Commission
pCi/g	picocurie per gram
PPE	personal protective equipment
ppm	parts per million
PVC	polyvinyl chloride
QEMSCAN	Quantitative Evaluation of Materials by SCANNing electron microscopy
RML	radioactive materials license
RO	reverse osmosis
SAP	Sampling and Analysis Plan
SBS	site-specific background standard
SDS	safety data sheet
SEM	scanning electron microscopy
SGR	spectral gamma ray
SMCB	San Mateo Creek Basin
SSE	Selective Sequential Extraction
STP	small tailing pile
TDS	total dissolved solids
Th	thorium
U	uranium
USEPA	United States Environmental Protection Agency
USGS	U.S. Geologic Survey

1. INTRODUCTION

The Homestake Mining Company of California (HMC) Grants Reclamation Project (GRP) is a former uranium mill located in the San Mateo Creek Basin in Cibola County, New Mexico, as shown on **Figure 1**. The mill operated from 1958 to 1990. Milling residue produced two on-site tailing piles: the small tailing pile (STP) and the large tailing pile (LTP), shown on **Figure 2**. Both tailing piles have influenced groundwater quality in the alluvial aquifer and shallow bedrock aquifer units immediately below and downgradient from the site. The site was placed on the United States Environmental Protection Agency's (USEPA's) Superfund National Priorities List (NPL) in September 1983 at the request of the State of New Mexico due to elevated selenium concentrations in the alluvial aquifer near the site. The Nuclear Regulatory Commission (NRC) administers a radioactive materials license (RML) held by the site (License No. SUA-1471); associated with this license are environmental restoration requirements that must be met prior to termination of the license. As a result of the NPL listing, the site's groundwater restoration activities are also being overseen under the USEPA's Superfund Program, in accordance with the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) (HMC 2012).

In 2016, the USEPA, with the assistance of the U.S. Geological Survey (USGS), initiated a reassessment of site background water quality standards at the GRP. Stakeholder groups have requested a better understanding of the site background standards and the occurrence of uranium in the alluvial system. Reassessment activities were conducted between June and October 2016 and included well reconnaissance, geophysics, and sampling of groundwater via micropurge, volume purge, and passive sampling techniques. HMC asked Arcadis U.S., Inc. (Arcadis) to collect split samples with the USGS during the 2016 sampling events.

Evaluation of the split sampling data has been ongoing; several meetings were held in 2018 with the USEPA, USGS, New Mexico Environment Department (NMED), and HMC regarding interpretations of the findings. The USEPA has sought additional information on the suitability of the monitoring well locations sampled in the alluvial aquifer upgradient from the site that were used to set site-specific background standards. Arcadis' interpretation of data collected during split sampling and during a subsequent soil investigation is that groundwater uranium concentrations in near-upgradient alluvial wells are attributed to naturally occurring uranium in soils. This interpretation is supported by data from the borehole installation adjacent to existing wells DD and DD2 (boreholes DD-BK and DD2-BK). Arcadis prepared a detailed report (Arcadis 2018a) that is included as an appendix in a white paper (Arcadis 2018b) that documents this conceptual site model (CSM). The white paper was provided to USEPA and NMED and the findings were discussed in subsequent meetings with the USEPA, NMED, HMC, NRC, and Arcadis. To address technical inquiries from the USEPA and NMED relating to the CSM, HMC has engaged Arcadis to perform a supplemental background investigation at the GRP. This investigation is comprised of four parts: 1) an initial geophysical survey to fill in data gaps relative to subsurface stratigraphy across the alluvial aquifer to the north (upgradient) of the site, 2) selection of locations for boreholes and well installation based on the geophysical survey results, 3) soil and groundwater sample collection and analysis, and 4) data summary and interpretation. The plan for this work is provided here.

1.1 Site History

The NRC licensed boundary of the GRP is 1,085 acres located 5.5 miles north of Milan, New Mexico, in Cibola County. The site is a former uranium mill, owned and operated by HMC, that processed ore from several mines. Milling operations were conducted from 1958 to 1990. Uranium milling was performed using a sodium carbonate solution (alkaline leach) in contact with crushed ore in large tanks. The leached uranium was chemically processed to prepare a concentrated form of uranium for shipment off site. The milling solid waste was managed in two tailing piles: the STP with 1.22 million tons of material covering 40 acres, and the LTP with 21.05 million tons of material covering 234 acres. The groundwater system at the GRP is comprised of an alluvial aquifer and underlying Chinle shale aquifer units, as well as the San Andres-Glorietta aquifer at depth; these systems are part of the lower San Mateo Creek Basin (SMCB). The tailing impoundments were not lined, and in 1976 elevated concentrations of selenium were noted in the alluvial groundwater underneath the LTP. In 1977 a groundwater management strategy was implemented, which was comprised of injection wells downgradient from the LTP to limit migration of impacted groundwater. Extraction wells were also installed, and the beginning of a groundwater restoration strategy was implemented from 1977 to 1982. In 1983 the site was placed on the NPL and a Corrective Action Program (CAP), as required by the RML, was submitted to the NRC in 1989 with updates submitted in 2006 and 2012 (HMC 2012). A comprehensive groundwater restoration strategy has been implemented at the site consisting of flushing of the LTP for control of the source of constituents of concern (COCs), to move pore water from the pile for collection and treatment, groundwater injection and extraction to limit migration of COCs, reverse-osmosis (RO) water treatment for all COCs, and water treatment using a flow-through zeolite system for uranium removal. The groundwater restoration program is authorized and regulated under NRC License SUA-1471 and NMED Discharge Permit DP-200.

The site COCs include selenium, uranium, molybdenum, sulfate, chloride, total dissolved solids (TDS), nitrate, vanadium, thorium-230, and combined radium-226 and radium-228. Groundwater restoration of the alluvial aquifer and underlying Chinle aquifers will proceed until Groundwater Protection Standards (GWPSs) are achieved. The 1989 CAP specified GWPSs for select COCs based on background water quality (i.e., site-specific background standards or SBSs) established through sampling one well in the alluvial aquifer upgradient from the site (well P). The characterization of background groundwater quality in the alluvial and Chinle aquifers was expanded in 2001 based on a set of upgradient wells (DD, ND, P, P1, P2, P3, P4, Q, and R for the alluvial aquifer) and evaluation of data over a 10-year period from 1995-2004 (nine wells, 124 data points). The updated upgradient wells were selected based on USEPA guidance such that the heterogeneity in background water quality entering the GRP was considered. New SBSs for selenium, uranium, sulfate, TDS, and nitrate were calculated according to USEPA guidance for the alluvial aquifer. In 2006, License Amendment #39 proposed the GWPSs for the COCs for each aquifer and included the SBS concentrations developed based on statistical approaches (along with standards for some COCs based on state or federal limits). The GWPSs (including a background concentration of uranium of 0.16 milligram per liter [mg/L] based on an upper 95th percentile of the data set) were accepted by NRC and agreed to by USEPA and NMED. Achieving these GWPSs is the goal of the current groundwater restoration efforts at the GRP.

1.2 Conceptual Site Model

The background water quality, and associated uranium concentration, is dictated by conditions in groundwater unrelated to the operation of the mill at the GRP, predominantly through natural processes. The natural occurrence of uranium in groundwater in the alluvial aquifer upgradient from the LTP and areas of known impacts from LTP seepage is described in a CSM. The CSM describes natural sources of uranium in groundwater and is applicable to the GRP footprint after groundwater restoration is complete, and as such, describes background conditions that will exist in groundwater after areas affected by LTP seepage are restored. The CSM is detailed in a white paper titled “Evaluation of Water Quality in Regard to Site Background Standards at the Grants Reclamation Project” (Arcadis 2018b). The CSM was prepared after completion of the 2016 background groundwater reassessment activities. It is based on the results of the split groundwater sampling event, historical water quality data, and the additional drilling in 2018 that included a soil lithological/mineralogical analysis and geophysical investigation of the alluvial system. The key component of the CSM is a description of natural sources of uranium to groundwater. Erosion and subsequent deposition of uranium-rich deposits from geological formations upgradient from the GRP were part of the formation of the alluvial system. These materials were deposited in discrete lithological horizons that exist in both the saturated and unsaturated zones. The uranium-rich lithologies present in the saturated zone have the potential to cause naturally increased localized uranium concentrations through oxidation and leaching of uranium-bearing minerals. The uranium-rich lithologies were emplaced through natural erosion and deposition of uranium-bearing minerals from bedrock sources lining the basin over hundreds to thousands of years. Depending on the location of eroded uranium-rich outcrops in the north and subsequent transport, and variations in groundwater recharge, the concentration of uranium in the alluvium varies in soils as it varies in groundwater. This results in significant heterogeneity in uranium concentrations in groundwater across the alluvial channel to the north of the LTP; this same heterogeneity in natural uranium concentrations in groundwater is expected to persist after groundwater restoration is complete. The CSM, shown on **Figure 3**, is summarized as follows:

- Weathering and erosion of exposed uranium-bearing formations (Morrison Formation [Jurassic], Dakota Sandstone [Cretaceous], and other associated uranium-rich formations to the north of the site) occurred over hundreds to thousands of years with eroded sediments containing high or low uranium concentrations depending on the source. The highest concentrations of uranium-bearing sediments may have been derived from the northwest based on the density of natural uranium deposits in that area.
- Alluvial material was transported and deposited over hundreds to thousands of years along the alluvial valley by a braided stream channel with varying depositional velocities, resulting in the formation of alternating clay, silt, sand, and gravel layers.
- The concentration of uranium in the deposited sediments depended on the erosional and depositional environment, with the presence of finer-grained sediments (and associated uranium-vanadium bearing clays, sulfide minerals, humate-organic particles, and uraninite/coffinite minerals) frequently associated with higher uranium concentrations.
- Regional groundwater recharge varies across the basin, with groundwater along the east being derived from lower-solute, low-uranium snowmelt from Lobo Canyon.

- Localized dissolved-phase uranium has leached from silt and clay-rich sediment layers within the alluvial sequence in response to natural groundwater geochemistry (elevated alkalinity and TDS), resulting in groundwater containing variable and natural uranium concentrations with depth and spatially across the alluvial channel.

1.3 Data Needs and Study Objectives

Prior work associated with the 2016 split sampling event, geophysics, and borehole development in 2018, has provided significant information on the geology, lithology, and mineralogy, including an enhanced understanding of the existence and form of natural uranium in alluvial sediments in the lower SMCB, immediately upgradient from the GRP. The work to date has resulted in the development of a CSM that describes natural sources of uranium in soil and groundwater, as described in the previous section and illustrated on **Figure 3**. The data have shown that wells used to evaluate the background water quality have not been affected by the LTP or by water flowing from the north with elevated constituent concentrations.

The 2018 borehole development and soil analysis work showed that lithology affects uranium content via grain size and sediment origin. Fine-grained soil is associated with higher uranium, and bedrock units with elevated uranium content (and known to harbor ore-grade uranium deposits) are located upgradient from the west side of the alluvial channel; however, the extent of the distribution of this material throughout the channel is currently not known. In addition, variation in hydraulic conditions in the channel is unknown and important because it affects the leaching of uranium out of naturally occurring minerals. Local heterogeneity of uranium in soils will translate into local variation in uranium concentration in groundwater depending on whether groundwater is fast or slow moving through these lithologic units.

Given that the expectation is that the alluvial channel to the north (upgradient) of the LTP is likely highly heterogeneous (based on variation in water quality across the channel), data are needed to demonstrate (or refute) this spatial variation in lithology and uranium content. This scope of work will fill this data need by showing the lithological and hydraulic heterogeneity across the channel and how they correlate with uranium concentrations in soil and groundwater.

Specific objectives of the 2019 background investigation to fill these data needs are as follows:

- Map alluvial channel geometry and zones containing high permeability coarse-grained materials.
- Estimate the uranium, thorium, and potassium content of the alluvium.
- Obtain lithological, chemical, and mineralogical data of sediments.
- Determine uranium concentrations in groundwater associated with (well screened within) coarse-grained, high-permeability and fine-grained, low-permeability sediments.

1.4 Work Tasks

Geophysical and lithological assessments, including installation of four new wells, and chemical and mineralogical analysis of sediments and groundwater, will meet the background investigation objectives as follows:

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- An Electrical Resistivity Tomography (ERT) assessment will provide high-resolution cross-sections of the channel geometry and sediment permeability; results will be used to inform the drilling phase of the program (**Section 2**).
- Downhole geophysical logging, including natural gamma, spectral gamma, and induction conductivity logging of new and existing boreholes/wells, will provide insight into the relationship between the lithology and uranium concentrations as well as guide interpretations of the ERT cross-sections (**Section 2**).
- Lithological assessment and sampling for metals content, mineralogy, and leachability of two new boreholes (BK1 on the western side/BK2 mid-channel of the alluvial basin) will provide a data set to compare to the 2018 boreholes and will guide installation of four new monitoring wells (at these two new boreholes) to target groundwater contained within coarse- and fine-grained sediments (**Section 3**).
- Installation and sampling of one well screened within the coarse-grained sediment and one well screened within the fine-grained sediment at each new borehole location will provide data to further refine and update the CSM for natural uranium placement and transport (**Section 3**).
- Lithological assessment and sampling for metals content, mineralogy, and leachability of one new borehole (BK3) on the eastern side of the alluvial channel will provide new information on the geological and mineralogical characteristics of this portion of the channel to compare to the western/mid side of the basin (**Section 3**).
- Lithological and geophysical assessment at a borehole (BK4) located immediately upgradient of the northwestern corner of the LTP to determine depth to bedrock as well as lithological characterization (**Section 3**).
- A report will be prepared to summarize the drilling, geophysical and lithological assessments, and soil and groundwater sampling results and evaluation (**Section 4**).

1.5 Site-Specific Health and Safety Plan

Site-specific emergency procedures, staff roles and required training, task-specific hazards, safety data sheets (SDSs), required monitoring and personal protective equipment (PPE), traffic control and communications plan, and other site-specific health and safety procedures (e.g., radiological site control and decontamination) are described in the Site-Specific Health and Safety Plan (HASP). The HASP also includes a formal risk assessment (FRA), conducted in collaboration with HMC, for the 2019 background investigation activities.

The HASP includes the following Job Safety Analyses (JSAs):

- Mobilization and demobilization
- Driving
- Site inspection (general safety)
- Utility clearance
- Surface geophysical resistivity assessment

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- Hand auguring
- Sonic drilling (includes drilling, sample collection, and well installation)
- Drilling, soil sampling, and well installation
- Downhole geophysical assessment
- Decontamination
- Sample cooler handling.

2. GEOPHYSICAL ASSESSMENTS

Geoscience professionals confront the challenge of understanding the broad context of subsurface conditions, particularly in environments where significant variability in the geologic conditions is evident. Direct observations of geologic materials with drilling technologies is the key means to obtain samples for visual description and a variety of physical and chemical testing procedures to better understand the nuances of the environment. However, direct sampling can be cost prohibitive when dealing with large-scale problems such as the study of the alluvial conditions at the GRP. A practical alternative is to obtain geophysical measurements that can be directly relatable to information obtained at the borehole scale, both along the ground surface and within borings and wells.

Arcadis has considered the specific geologic conditions in the alluvial setting and determined that a viable and cost-effective surface geophysical method to broadly image the subsurface is electrical resistivity imaging along 2-dimensional cross-sections, or tomography for short. The goal of the ERT is to obtain a robust, high-density set of apparent resistivity readings that span the alluvial channel and penetrate to a depth to encounter the underlying bedrock. The raw ERT data sets will be subjected to data processing, which yields a true model of the electrical resistivity of the subsurface. Data obtained at the borehole scale will be incorporated into the interpretation of the ERT images to guide geologic interpretations at and between boreholes. The outcome is expected to provide a direct, continuous image of the bedrock surface beneath the alluvium and internal characteristics of the alluvium at the scale of the geologic sequences or packages of similar lithofacies. Hydrogeologic conditions (degree of saturation and groundwater chemistry) are also expected to be evident because it is essentially pore waters that carry the electrical current in the subsurface.

In addition to the surface geophysical work using ERT, Arcadis has included geophysical measurements within boreholes and wells to provide supporting information and detail at the borehole scale. First, measurements will be made to guide the interpretation of the surface geophysical ERT work. Continuously recorded values of the electrical resistivity of the alluvium outside the well will be gathered in the downhole geophysical phase of work. The technology Arcadis will use to make these measurements does not require direct contact with the alluvium and, therefore, measurements will be made in polyvinyl chloride (PVC) monitoring wells. For the wells located along the ERT section lines, the borehole measurements will be used as *a priori* information to constrain the ERT modeling process as part of the effort to interpret the ERT images. In addition to borehole-scale electrical resistivity measurements, continuous natural gamma logs will also be obtained, which will be invaluable in interpreting the geologic conditions. Finally, borehole-scale measurements of the gamma ray spectra will be made to yield information about the concentrations of potassium, uranium, and thorium in the alluvium. This information will be integral to the interpretation of the origins of the sedimentary facies and the variability of naturally occurring uranium, and, in the case of existing wells (specifically DD, DD2, MV, ND, and Q), will provide information that is otherwise not easily obtained without additional drilling and testing.

2.1 Electrical Resistivity Tomography Assessment

Arcadis will use an ERT assessment to map alluvial channel geometry and the internal variations in the alluvium. The ERT data will be used to inform the drilling phase of the program (see **Section 3**) to determine well positioning and well construction details, including the desired well screen interval.

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The key benefit is that this ERT assessment will provide a continuous, broad context for the correlations of the detailed information found within individual boreholes, leading to a more comprehensive and defensible interpretation of the alluvial sediments within the stratigraphic constraints associated with the basin required to outline heterogeneity and potential preferential flow pathways. This is important given the hypothesis that uranium concentrations could be influenced by localized variability tied to the lithology and sediment provenance.

An example of the typical output from an ERT survey is provided in **Exhibit 1**, in which the heterogeneity of alluvial sediments is highlighted. Such an ERT cross-section shows where the highest and lowest hydraulic conductivity zones are based on their corresponding electrical resistivity characteristics in the subsurface and can be very valuable for mapping preferential flow pathways for groundwater based on the distinct electrical resistivity properties of various types of alluvial materials.

Arcadis will conduct the ERT assessment as follows:

- Electrical resistivity data sets will be collected along two roughly parallel east-west transects that span the alluvial channel, where each transect is approximately 7,600 feet in length. The planned approximate locations of the ERT transects are shown on **Figure 4**.
- The ERT setup will utilize 112 electrodes with 6-meter (19.7-foot) inter-electrode spacing. The effective imaging depth of this configuration is approximately 150 feet below ground surface (bgs), which is sufficiently deep to image bedrock in this area.
- A SuperSting R8™ resistivity meter manufactured by Advanced Geosciences Inc. (or equivalent) will be used to collect ERT data.
- A combined dipole-dipole and strong gradient array type will be used to collect ERT data. These combined arrays provide optimal horizontal and vertical sensitivity required to capture the complexities of the stratigraphic environment.
- A total of five overlapping ERT data sets will be collected along each 7,600-foot transect line. Following field data collection, data will be compiled and inverse-modelled to create an electrical resistivity cross-section of the alluvial channel. The RES2DINV software program by Geotomo Software will be used to reduce and inverse-model ERT data. New and existing borehole geophysical (induction conductivity) data will be used to constrain (*a priori*) the resistivity models.
- The location of the electrodes in each ERT transect will be mapped with a high precision global positioning system (GPS) surveying unit.
- The geophysical resistivity tomography work will be performed prior to the installation of any additional boreholes and/or wells as information gained from the sections will be used to more effectively target the drilling assessment(s), based on the lithological interpretation. To the extent possible, existing borehole data will be used to interpret the ERT results, including recent data collected from boreholes DD-BK/DD2-BK as well as newly collected borehole geophysical data from existing wells.

Additional details about ERT field data collection methods and data processing are described in the Sampling and Analysis Plan (SAP) for the 2019 Background Investigation at the GRP, included as **Appendix A**.

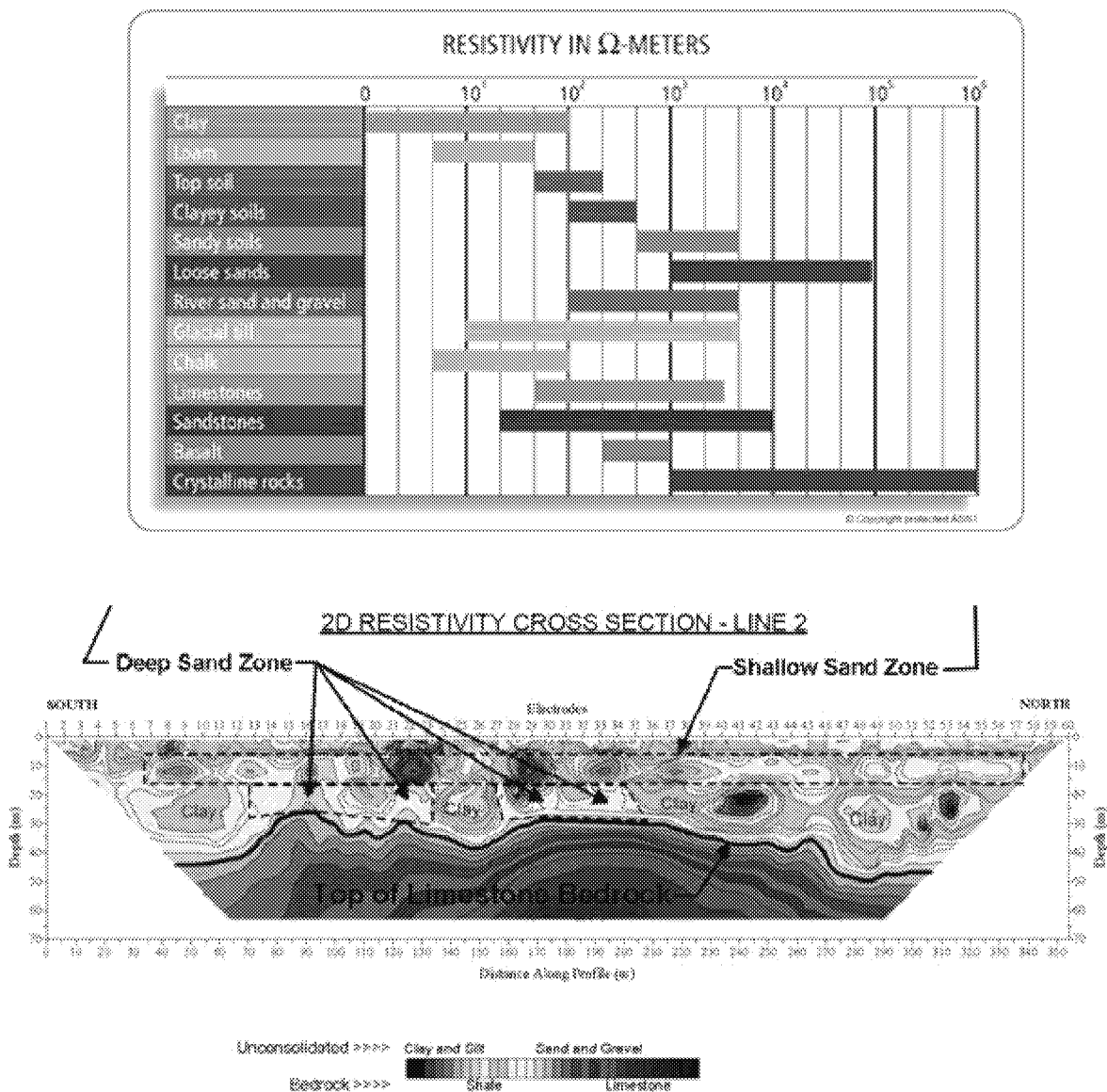


Exhibit 1. Example electrical resistivity tomography results

Resistivity values listed for various lithologies (top) and shown in an actual cross-section (bottom) illustrate how the ERT values can map in-situ geology of unconsolidated lithologies as well as bedrock. Colors in the actual cross-section (bottom) indicate lithologies as listed with the legend in the bottom image and do not correspond with the arbitrary colors shown in the top chart.

2.2 Downhole Geophysical Logging

Downhole geophysical logging has been integral to recent interpretations of the geologic, hydrogeologic, and geochemical conditions within the alluvium (Arcadis 2018b; Harte et al. 2019). Previously existing and newly collected downhole geophysical data will provide a common set of detailed, quantitative, in-situ

measurements to link interpretations between visual geologic descriptions and the large-scale ERT cross-sections included in this work plan. Key uses for downhole geophysical data are envisioned to include:

- Lithologic and stratigraphic interpretations in specific locations and along lines of the cross-section to allow inclusion of new and existing wells in the development of the broad interpretations of depositional environments within the alluvium;
- Determination of in-situ concentrations of potassium (K), uranium (U), and thorium (Th) within the alluvium in a continuous manner useful for 1) identifying relationships between naturally occurring uranium and litho-stratigraphic conditions, mineralogy, and geochemical parameters, and 2) interpretation of the provenance of the alluvial sediments using the Th-K ratios and well-established analysis methods (Schlumberger 2009); and
- Calibration and constraint of the ERT inverse models to optimize the geologic interpretations of the alluvium and bedrock. Downhole geophysical data will also provide a direct measure of resistivity conditions and allow for estimation of 1) vertical resolution and uncertainty in the ERT models, and 2) hydraulic parameters such as water saturation, porosity, and possibly grain-related parameters such as grain cementation and tortuosity.

The locations of existing and new wells planned for downhole geophysical logging are illustrated on **Figure 4 (superseded by Appendix C for borehole locations)**. The SAP for this work, included as **Appendix A**, provides detailed descriptions of the logging equipment as well as the data collection and analysis procedures. The types of geophysical data that will be collected are described below.

2.2.1 Method Descriptions

Arcadis will gather three basic types of downhole geophysical data: natural gamma ray (NGR), electrical conductivity (EC), and spectral gamma ray (SGR). All three methods have proven to provide useful information about the alluvial conditions. Moreover, these methods are chosen because the data can be obtained within non-metallic wells. Below are the descriptions each of these methods.

Natural Gamma Ray

NGR logging is a commonly used method to interpret lithology in stratigraphic sediments and rocks. It yields the gross count of natural gamma rays emitted from radioisotopes in the formation, the most common of which is potassium-40 (^{40}K). Orthoclase, biotite, muscovite, illite, smectite, and bentonite are common potassium-bearing minerals that contribute gamma rays. In mature sedimentary environments, coarse materials tend to be depleted of potassium-bearing minerals, and potassium-bearing clay minerals tend to dominate the natural gamma signal in the fine-grained portions of the sediments. Immature coarse-grained sediments that contain significant concentrations of lithic fragments and mineral clasts derived from igneous and metamorphic rocks (felsic to intermediate composition in particular) may be indistinguishable from fine-grained potassium-rich clays, and one of the interpretational pitfalls can be misidentification of lithologies. For this reason, it is a best practice to also collect complementary geophysical data such as point resistance, normal resistivity, or inductive EC because these methods yield information that is directly related to water saturation, water conductance (TDS), porosity, grain-related parameters, and potentially permeability.

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Collecting NGR data is relatively simple. No calibration is required in the field (the vendor supplies a certificate of calibration), and the rate of data collection in the hole is relatively high, between 10 and 15 feet per minute. A single value of the total counts per second of gamma rays is stored for each digitized increment (generally 0.1 to 0.3 foot per data point is used).

There is a randomness to the rate of radioactive decay over a short period of time; therefore, raw NGR logs are typically quite noisy. The standard practice for suppressing the random component of the signal to reveal the central trend of the rate of gamma emissions is to apply a weighted average filter to the raw data. Generally, no other processing of NGR data is needed.

The graphical presentation NGR data are useful to identify litho-stratigraphic patterns which can be interpreted in the context of the depositional environment. Subtle vertical changes in clay content not easily captured visually, for example in a fining upwards sequence associated with a meandering stream environment, can be observed in NGR data.

Electrical Conductivity

The inductive EC log provides additional insight regarding the lithology and complements the NGR data, helping to avoid pitfalls as noted above. Unlike NGR, the logging methods that quantify the electrical resistivity or conductivity (the inverse of electrical resistivity) are generally not sensitive to mineral species (in coarse clastics), but instead are sensitive to 1) the specific geometric parameters describing the interconnected grain to grain porosity; 2) the degree of saturation of the fluids that occupy the pore spaces, whether air, water, or both; and 3) the electrical conductance of the groundwater in the pores, which often is strongly related to the TDS. The logging activities will occur in non-metallic wells rather than an open hole; therefore, the best method for this application is the inductive EC method (resistivity logging requires a fluid-filled hole).

One of the most notable responses of EC data is the increase in conductivity within the saturated zone. Once in saturated conditions, generally the less conductive materials tend to be "clean" mixtures of coarse-grained materials low in clays. Within the domain of coarse-grained materials, well-graded/poorly sorted coarse clastics tend to be less conductive than well-sorted/poorly graded coarse clastics. These relationships reflect the combined effects of the grain-related parameters. Note that, if the composition of the coarse materials is uniform and the variability is mainly related to grain-size distribution, the NGR log will likely have only minor variability in a relative sense.

As a rule, the most conductive materials (least resistive) clastics tend to be fine-grained mixtures of silt and clay. Note that clay minerals have a net negative surface charge and interact with ionic species within the pore waters. When electrical current is applied to clays during EC measurements, the loosely bound cations and anions in the clay pores are freed to contribute to the current flow and, as a result, clay-rich sediments are generally very conductive. A generalization can often be made that fine-grained clastics are thus both relatively high in natural gamma rays and EC.

Deviations from the generalized relationships between NGR and EC data can be useful to identify materials in which the source of natural gamma rays is a radionuclide other than ^{40}K (e.g., in uranium-rich materials). In the case of unexpected EC variations, differences in the groundwater chemistry may be the cause. And, as mentioned above, if the clastics are immature, relatively close to the source (e.g., arkose)

clastic material may have an EC response corresponding to coarse-grained clastics yet an NGR signature that is akin to clay-rich sediments.

Spectral Gamma Ray

Unlike NGR, which is a gross count of total gamma rays and is represented by a single value, SGR quantifies a broad spectrum of gamma rays, spanning 0 to 3 million electron volts (MeV) of gamma ray energy. Since specific associations between discrete, diagnostic gamma ray energies and radioactive elements exist, in the naturally occurring radioisotope scenario, there is a dominant set of peaks for the most common elements follows:

- Potassium-40: 1.46 MeV
- Uranium-238: 1.76 MeV
- Thorium-232: 2.62 MeV

Collection of SGR data is generally done initially using a continuous measurement of the gamma spectra at the rate of 1 to 3 feet per minute. This is termed dynamic SGR, and the intent is to identify gross trends in the distribution of K, U, and Th. After interpretation of the dynamic SGR, the well is re-entered and the SGR probe is lowered to specific depths where full quantification of the gamma spectra is desired. This process is termed static SGR. Generally, measurements of the gamma spectra at a given depth are made for a duration of 15 minutes or more. These discrete, data-rich spectra records are summed together (stacked) to greatly decrease random noise and enhance signal.

After data stacking, a modeling process is used to estimate the activity-based concentration (picocuries per gram [pCi/g]) of each of the three elements by 1) isolating, or stripping, the peaks for each element and 2) measuring the height of each peak at the given gamma ray energy levels to arrive at the activity-based concentrations. The mass-based concentration of each element can be calculated from activity-based units using the following relationships empirically determined with specific standard boreholes in which conditions are known. One such set of equations in the public domain is from Appendix A of Stromswold (1994):

- 1 percent (%) K = 8.371 pCi/g of K
- 1 parts per million (ppm) U = 0.3337 pCi/g of U
- 1 ppm Th = 0.110 pCi/g of Th

The dynamic and static SGR results are plotted graphically on the borehole geophysical log along with the other geophysical and geological variables.

Other analysis of the SGR data may also be useful, including the cross-plotting of Th and K. There is a well-studied relationship useful for determining details about the composition of the clastic materials beyond what is possible with natural gamma alone: the overall degree of maturity and weathering of the clastic sediments are reflected in the relative proportions of K and Th in the clays created during the chemical weathering process. Essentially, K is removed from the system as the sediment matures,

leaving increasing concentrations of Th, which is very resistant to weathering. **Exhibit 2** illustrates how Th/K can be used to infer the mineralogy of the formation¹.

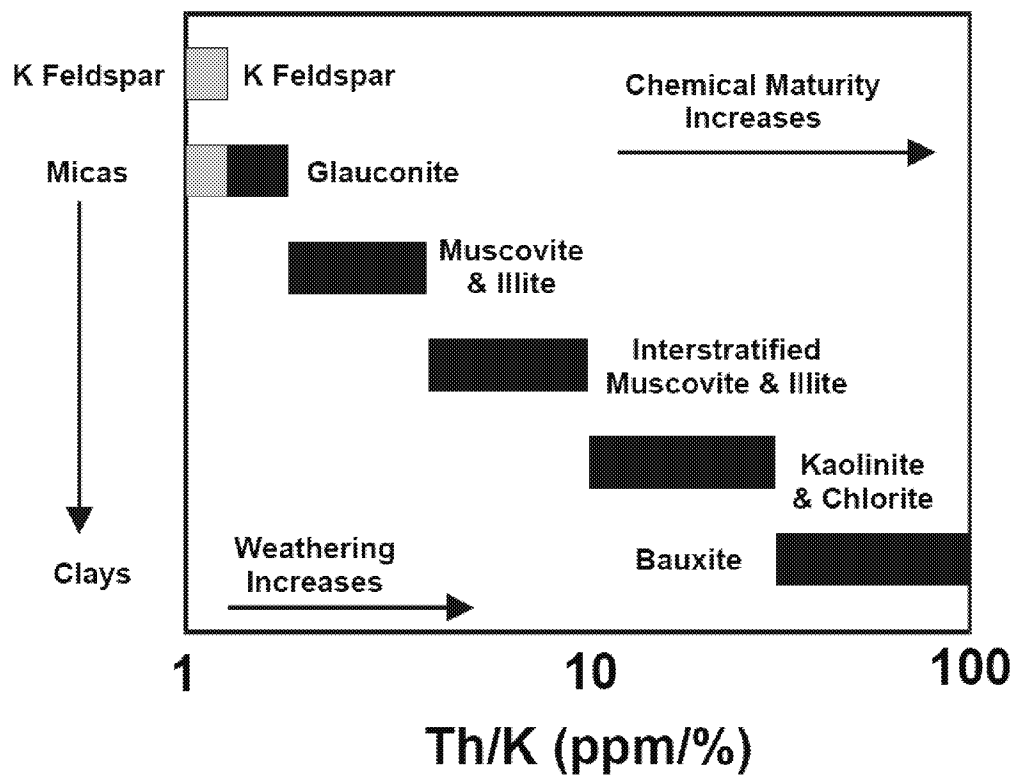


Exhibit 2. Thorium/potassium ratio plot for mineral identification using spectral gamma ray data

¹ http://homepages.see.leeds.ac.uk/~earpwjg/PG_EN/CD%20Contents/GGL-66565%20Petrophysics%20English/Chapter%2012.PDF

3. LITHOLOGICAL ASSESSMENT AND INSTALLATION OF MONITORING WELLS

Two locations will be selected for lithological assessment and groundwater monitoring well installation along the geophysical resistivity lines (BK1 and BK2). Soil sampling during advancement of the boreholes will provide geochemical data from both fine-grained and coarse-grained sediments. The groundwater monitoring wells will be installed with short screen intervals separately screened across the fine-grained and coarse-grained sediments, to assess the associated geochemical trends in groundwater.

The results will be used to assess the CSM for natural uranium placement and transport. Groundwater data reflecting that higher uranium concentrations are associated with the finer-grained sediments would indicate that uranium was naturally emplaced during fluvial deposition and is being released into groundwater locally by natural processes.

Conversely, groundwater data reflecting that higher uranium concentrations are associated with the coarser-grained, high hydraulic conductivity sediments could suggest that uranium in groundwater may be present because of regional groundwater sources.

Drilling and installation of the groundwater monitoring wells will be conducted in accordance with the New Mexico Office of the State Engineer Rules and Regulations Governing Well Driller Licensing, Construction, Repair, and Plugging of Wells (19.27.4 New Mexico Administrative Code). The boreholes will be advanced using rotary sonic drilling technique. All drill rig equipment will be decontaminated before drilling operations are begun.

The lithological assessment and monitoring well installation program at each of two sites (precise locations to be determined) along the ERT transects will consist of the following:

- Borehole drilling, lithological assessment, and sampling
- Downhole geophysical assessment
- First groundwater monitoring well installation (screened across coarse sediments)
- Second groundwater monitoring well installation with approximately 50 feet from the first well (screened across fine sediments).

3.1 Borehole Drilling, Lithological Assessment, and Sampling

Six boreholes will be advanced through alluvial materials and 5 feet into bedrock (two at BK1 and BK2, and one each at BK3 and BK4). A geologist will continuously observe all drilling operations, and representative samples of the drill cuttings will be collected and logged at regular intervals during drilling in accordance with ASTM International (ASTM) Designation D2488. Lithologic descriptions will include soil type, color, grade, sorting, matrix, accessory minerals, hardness, and an estimation of moisture content. Observations of the drilling progress will also be captured and logged.

Bedrock is anticipated at a depth of approximately 95 to 105 feet, based on previous drilling in the area. Core will be recovered for the entire borehole length, lithologically logged, and sampled for analysis of metals content, mineralogy, and leachability.

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Arcadis will sample sediments for chemical and mineralogical analyses from one borehole at each location based on lithological characteristics and with the intent to obtain representative data for each borehole. Through these analyses, a data set will be generated for these boreholes to compare to data previously collected from boreholes DD-BK and DD2-BK.

Arcadis will perform the following analyses at boreholes BK1, BK2 (on one borehole at each of these locations), and BK3:

- Total metal and radionuclide content by USEPA Method 3050B (hydrochloric/nitric acid digestion) and USEPA Method 6020 (inductively coupled plasma mass spectrometry) – this will provide the concentration of “environmentally accessible” major and trace elements;
- Selective Sequential Extraction (SSE) to evaluate the mineralogy that contains elements of interest – this will include the following fractions: water soluble, exchangeable, carbonate bound, oxide bound, organic bound, and recalcitrant. The extraction chemistries will proceed based on the SSE protocol outlined in Tessier et al. (1979);
- Total organic carbon content on a subset of samples that show the highest uranium concentrations in order to understand the association of uranium with organic carbon, which can retard uranium movement in the subsurface;
- Separation of sediment particles into “light” and “heavy” fractions and analysis of total metals and radionuclides by USEPA Method 3050B with 6020 – this will provide an understanding of the association of uranium and other elements with density-specific mineral fractions;
- Light-microscopy (petrographic microscopy) to evaluate mineralogical characteristics;
- X-ray diffraction to determine major mineralogical content;
- Sulfur stable isotopes on the sediments. Possible pre-processing may be conducted to target sulfides in the samples; and
- Electron/x-ray microscopy/spectroscopy. Prior scanning electron microscopy (SEM) analyses on sediments from boreholes DD-BK and DD2-BK yielded important information about the minerals present, specifically pyrite and oxidized iron sulfides (iron oxyhydroxides), phases that can harbor uranium. The SEM analyses also demonstrated the presence of both reduced and oxidized mineral forms in the sediments and showed that the aquifer environment is dynamic, with redox interfaces present that can result in the dissolution of uranium from natural minerals. One of the challenges was the direct detection of uranium due to its presence at relatively low concentrations. Arcadis will use Quantitative Evaluation of Materials by SCANNing electron microscopy or “QEMSCAN” instead, for its ability to automate SEM data collection and improved (better resolution) energy dispersive x-ray spectroscopy data.

Details of the soil sampling program and methods are provided in the SAP, included as **Appendix A**.

3.2 First Well Installation (Coarse Sediments)

The coarse sediment groundwater monitoring well will be installed first during the field activities at each location (BK1 and BK2). The monitoring well borehole will be advanced using a minimum 6-inch-diameter

drilling bit. The borehole will be terminated approximately 5 feet beneath the bedrock interface, with the final borehole depth anticipated to be approximately 105 feet bgs. The final borehole depth will depend on the bedrock interface at the time of drilling.

Anticipated well construction details are presented in **Table 1**, and a well construction diagram is presented on **Figure B-1 in Appendix B**. The well will be installed with a 2-inch Schedule 40 PVC casing that extends into the bedrock to enable the downhole geophysics to be conducted, but it will have a short screen interval (5 to 10 feet in length) for targeted groundwater collection. The screen slot size will be 0.01-inch factory slotted screen.

The groundwater monitoring well screen interval will be positioned to target coarse, higher-permeability sediments. The screen placement will be based on the surface geophysical resistivity assessment and refined by core lithological logging during drilling. The base of the well will be sealed with bentonite chips up to within 3 feet of the base of the screen. A 2/12 filter pack sand will be placed in the annulus around the screen to approximately 3 feet above the top of the screen, followed by 5 feet of bentonite chips. The remaining annulus will be filled to the ground with a Portland neat cement grout with 5% bentonite. The exact screen interval and well design will be determined in the field based on the lithology encountered and depth to bedrock.

3.3 Second Well Installation (Fine Sediments)

The fine sediment groundwater monitoring well will be installed second during the field activities at each location (BK1 and BK2). The construction of this groundwater monitoring well will be based on the results of the downhole geophysical assessment, with the screen interval targeting fine-grained sediments.

Well construction details are presented in **Table 1**, and a well construction diagram is presented on **Figure B-2 in Appendix B**. The groundwater monitoring well will be installed with a 2-inch Schedule 40 PVC casing, with a short screen interval (5 to 10 feet in length) for targeted groundwater collection. The screen slot size will be 0.01-inch factory slotted screen. A 2/12 filter pack sand will be placed in the annulus around the screen to approximately 3 feet above the top of the screen, followed by 5 feet of bentonite chips. The remaining annulus will be filled to the ground surface with a Portland neat cement grout with 5% bentonite. The exact screen interval and well design will be determined in the field based on the lithology encountered and depth to bedrock.

3.4 Downhole Geophysical Assessment

As described previously, Arcadis will conduct natural gamma, spectral gamma, and induction conductivity logging in the newly installed boreholes BK1, BK2, BK3, and BK4, sited by the ERT results, cased with 2-inch Schedule 40 PVC riser. Spectral gamma will be performed in two modes: dynamic and static, resulting in data that will provide direct estimation of the K, U, and Th concentrations in the alluvium. The dynamic spectral gamma data will be used to select the static spectral gamma logging locations, and in turn the static spectral gamma will be used to decide which samples to select for laboratory testing. During the same mobilization as the drilling and logging performed at two new locations, downhole geophysical assessments will be conducted on the first borehole at two time periods:

- Initially when the first borehole has reached its total depth and the drill casing is still in place prior to well installation, logging for natural gamma/spectral gamma will be conducted. This will prevent

interference by well materials that will be present after well construction (such as bentonite) on the gamma data.

- After installation of the well for the remaining geophysical parameters (induction conductivity).

A discussion of downhole geophysical methods was already provided earlier in this work plan, and additional details are provided in the SAP (**Appendix A**).

3.5 Well Development

The newly installed wells will be developed no sooner than 48 hours after installation to allow adequate time for the well seals to cure. The wells will be developed by surging, bailing, and pumping to remove fine sediment introduced during drilling and/or well construction. During well development, the volume of water extracted and field parameters will be measured, including pH, EC, turbidity, oxidation-reduction potential, dissolved oxygen, and temperature. Development will continue until the turbidity is significantly reduced, targeting readings are less than 5 nephelometric turbidity units, and parameters have stabilized (less than 10% variation in readings).

4. DATA ANALYSIS AND REPORTING

Arcadis will perform the following data evaluation and reporting activities related to the geophysical assessment and borehole/well installation and sampling:

- Model the spectral gamma ray data to calculate the estimated K, U, and Th content of the alluvium. The dynamic data will be reviewed in the field to select the specific static measurement locations. The static data will reflect a higher accuracy and precision than the dynamic data.
- Produce detailed, cross-sectional views of the ERT data to depict the distribution of electrical resistivity variations in alluvial channel sediments and underlying bedrock.
- Produce borehole geophysical graphic logs using WellCAD portraying the geophysical results, visual lithology descriptions, and relevant analytical and mineralogical results to facilitate comparison of the geophysical, observational, and laboratory data.
- Process and evaluate the drilling, geochemical, and geophysical data, comparing lithological variations, geophysical variations, and uranium concentrations with depth.
- Evaluate the borehole sediment chemical and mineralogical results and groundwater results to further refine and update the CSM regarding sources of uranium and other constituents to groundwater upgradient from the GRP.
- Prepare a report to summarize the drilling, soil sampling, geophysical assessment, and data evaluation results. The report will include boring logs and figures of the final boring locations and geochemical results.

Additional information about data collection and data processing is provided in the SAP, included as **Appendix A**.

5. REFERENCES

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WORK PLAN TABLE

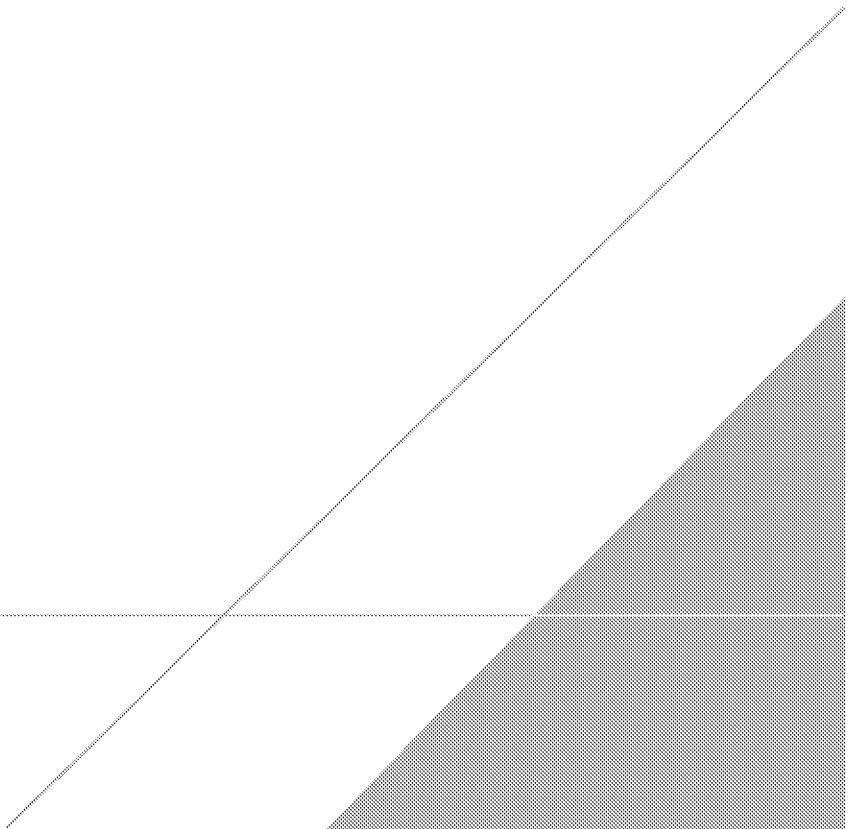


Table 1
Proposed Monitoring Well Construction Details
2019 Background Investigation
Grants Reclamation Project

Location	Well ID	Use	Anticipated Depth to Water (feet)	Approximate Borehole/Well Depth (ft bgs) ¹	Borehole Diameter (inches)	Well Construction Details
Location Along Geophysical Line Number 1 (well pair located within 50 feet of each other)	GF1-CS	Lithological Assessment, Geophysical Logging, and Coarse Sediment Groundwater Monitoring Well	45	105	>6	2-inch PVC Schedule 40 blank casing, with 5-10 feet of 0.010-inch screen, bentonite chip from base borehole to within 3 feet below screen, sand filter pack place adjacent to the screen extending 3 feet above the screen, 5 feet of chip on top of screen, and Portland cement grout with 5% bentonite to surface (installed via tremmie pipe), surface completion with well riser and above ground box with 2-inch J-plug.
	GF1-FS	Fine Sediment Groundwater Monitoring Well	45	70	>6	2-inch PVC Schedule 40 blank casing, with 5-10 feet of 0.010-inch screen, sand filter pack from the base of the well adjacent to the screen extending 3 feet above the screen, 5 feet of chip on top of screen, and Portland cement grout with 5% bentonite to surface (installed via tremmie pipe), surface completion with well riser and above ground box with 2-inch J-plug.
Location Along Geophysical Line Number 2 (well pair located within 50 feet of each other)	GF2-CS	Lithological Assessment, Geophysical Logging, and Coarse Sediment Groundwater Monitoring Well	45	105	>6	2-inch PVC Schedule 40 blank casing, with 5-10 feet of 0.010-inch screen, bentonite chip from base borehole to within 3 feet below screen, sand filter pack place adjacent to the screen extending 3 feet above the screen, 5 feet of chip on top of screen, and Portland cement grout 5% bentonite to surface (installed via tremmie pipe), surface completion with well riser and above ground box with 2-inch J-plug.
	GF2-FS	Fine Sediment Groundwater Monitoring Well	45	70	>6	2-inch PVC Schedule 40 blank casing, with 5-10 feet of 0.010-inch screen, sand filter pack from the base of the well adjacent to the screen extending 3 feet above the screen, 5 feet of chip on top of screen, and Portland cement grout 5% bentonite to surface (installed via tremmie pipe), surface completion with well riser and above ground box with 2-inch J-plug.

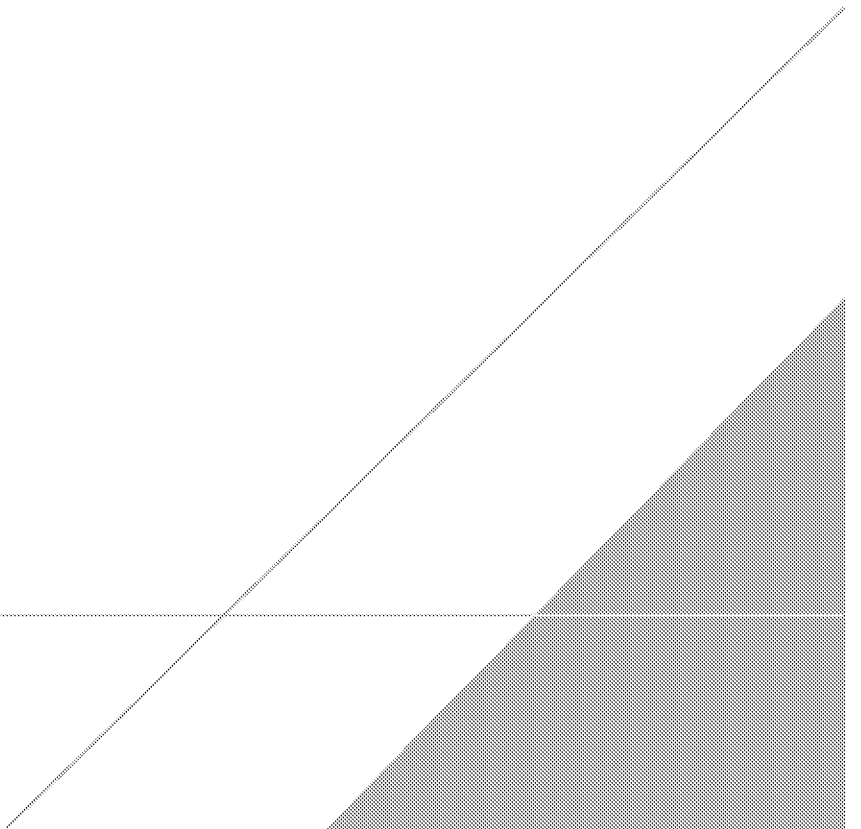
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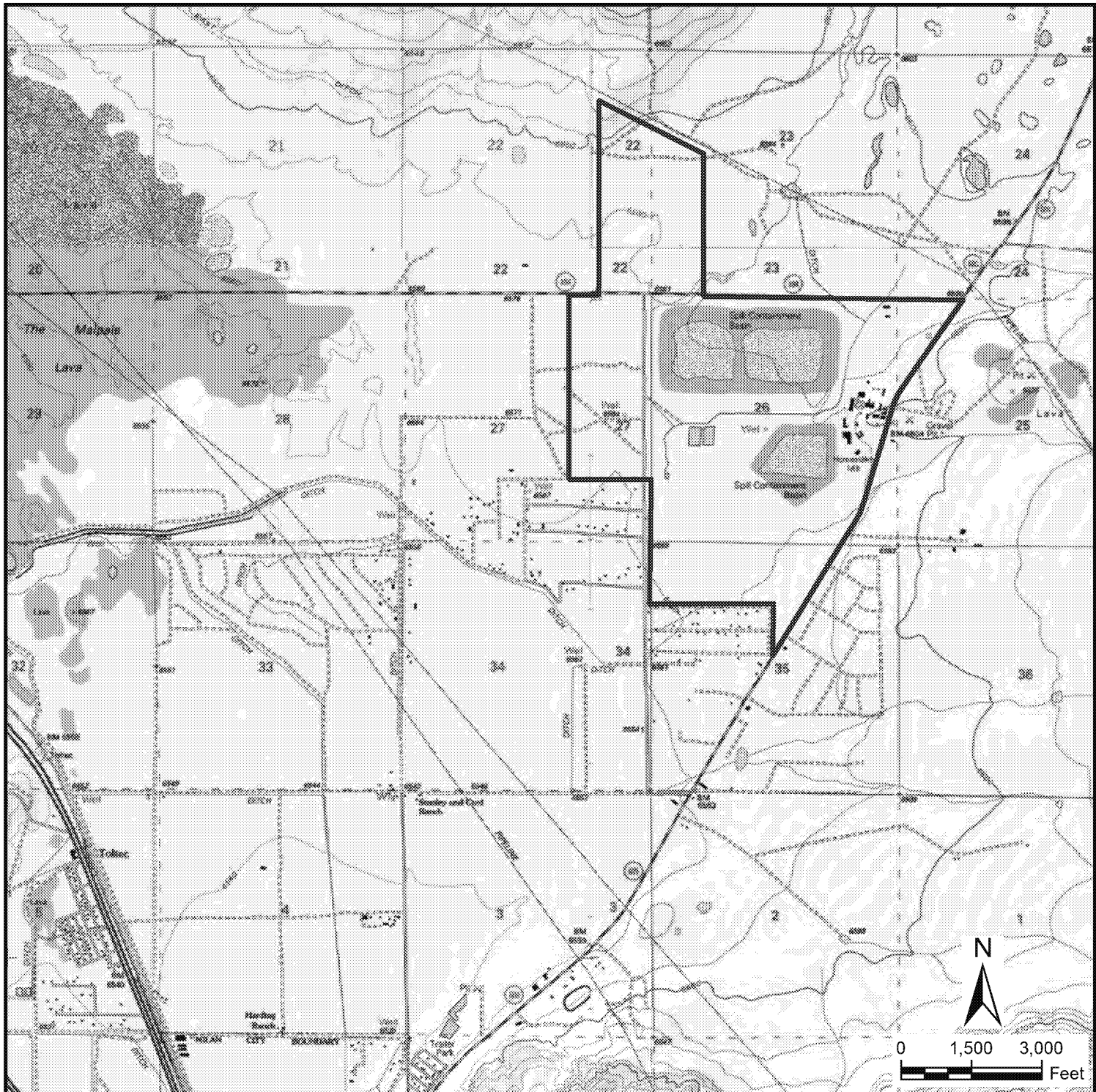
¹All depths are approximated and will be determined in the field based on conditions encountered.

ft bgs = feet below ground surface

PVC = Polyvinyl chloride

WORK PLAN FIGURES

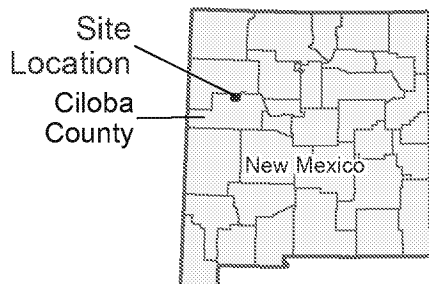




Source: USA Topo Maps, serviced by ESRI ArcGIS Online

LEGEND:

 Nuclear Regulatory Commission License Boundary



WORK PLAN
2019 BACKGROUND INVESTIGATION
GRANTS RECLAMATION PROJECT

SITE LOCATION MAP



FIGURE
1



●

RO Sampling Point

○

Alluvial Aquifer Well

●

Upper Chinle Aquifer Well

●

Middle Chinle Aquifer Well

●

Lower Chinle Aquifer Well

●

2018 Borehole Location

▲

Supplemental Monitoring Well Locations for EP-3

▲

Alluvial Borehole

ND

Wells used to derive site-specific background concentrations

DD-BK

2018 Borehole Location

N

0

2,000

4,000

SCALE IN FEET

Basemap features from:
Hydro-Engineering, LLC, 2011

WORK PLAN
2019 BACKGROUND INVESTIGATION
GRANTS RECLAMATION PROJECT

SITE LAYOUT

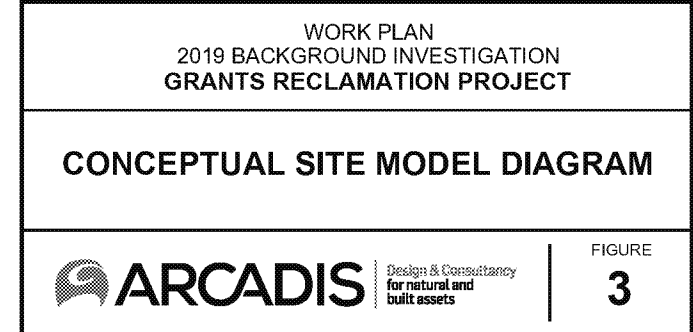
ARCADIS

FIGURE

2

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LEGEND

Existing alluvial aquifer wells planned for downhole geophysical logging including natural gamma, spectral gamma, and induction conductivity (see Note 1)

New Borehole Locations

Alluvial Borehole

Fault

Proposed Electrical Resistivity Line

DD-BK

2018 Borehole Location

Subcrop* of Upper Chinle Alluvium Overlies Sandstone

Saturated Alluvium

Subcrop* of Middle Chinle Alluvium Overlies Sandstone

Saturated Alluvium

Unsaturated Alluvium

* Subcrop boundary dashed where inferred.

Notes:

- 1) Only spectral gamma data will be collected for wells DD, DD2, MV, ND, and Q.
- 2) Four new borehole locations will be advanced along the resistivity lines; the locations shown on this map are based upon completion of the ERT survey.
- 3) Four new wells (at locations BK1 and BK2) will undergo downhole geophysical assessment via natural gamma, spectral gamma, and induction conductivity, boreholes BK3 and BK4 will also undergo geophysical assessment.

N

0

2,000

4,000

SCALE IN FEET

Basemap features from:
Hydro-Engineering, LLC, 2011

WORK PLAN
2019 BACKGROUND INVESTIGATION
GRANTS RECLAMATION PROJECT

**PROPOSED GEOPHYSICAL ASSESSMENTS
AND BOREHOLE LOCATIONS**

ARCADIS

FIGURE
4

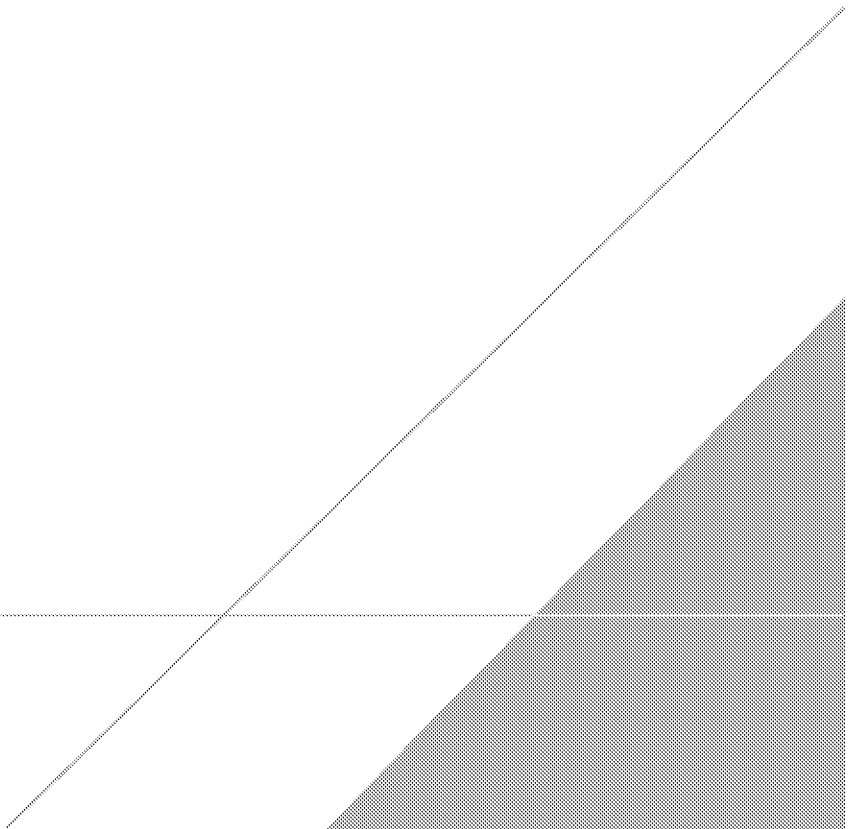
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WORK PLAN

APPENDIX A

Sampling and Analysis Plan





Homestake Mining Company of California

SAMPLING AND ANALYSIS PLAN: 2019 BACKGROUND INVESTIGATION

Grants Reclamation Project
Grants, New Mexico

May 2019

**SAMPLING AND
ANALYSIS PLAN:
2019 BACKGROUND
INVESTIGATION**

Grants Reclamation Project
Grants, New Mexico



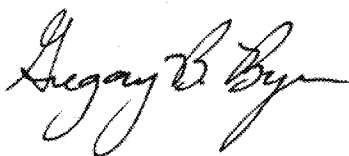
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May 2019

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Jeff Gillow, PhD
Principal

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APPENDICES

Appendix A	Quality Assurance Project Plan
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ACRONYMS AND ABBREVIATIONS

2D	two-dimensional
Arcadis	Arcadis U.S., Inc.
ASTM	ASTM International
°C	degrees Celsius
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
COC	constituent of concern
cps	counts per second
CSM	conceptual site model
DQO	data quality objective
EDD	Electronic Data Deliverable
EDS	energy dispersive x-ray spectroscopy
EM	Electromagnetic
ERT	electrical resistivity tomography
GPS	global positioning system
GRP	Grants Reclamation Project
HASP	Health and Safety Plan
HMC	Homestake Mining Company of California
IDW	investigation-derived waste
IT ²	Isotope Tracer Technologies
kΩ	kiloohm
LTP	Large Tailings Pile
MS	matrix spike
MSD	matrix spike duplicate
NGR	natural gamma ray
NMED	New Mexico Environment Department
PPE	personal protective equipment
PVC	polyvinyl chloride
QA/QC	quality assurance/quality control
QAPP	Quality Assurance Project Plan

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QEMSCAN	Quantitative Evaluation of Materials by SCANNing electron microscopy
SAP	Sampling and Analysis Plan
SEM	scanning electron microscopy
SGR	spectral gamma ray
Site	Grants Reclamation Project located in Grants, New Mexico
SOP	Standard Operating Procedure
SSE	Selective Sequential Extraction
USEPA	United States Environmental Protection Agency
USGS	U.S. Geological Survey

1 INTRODUCTION

This 2019 Background Investigation Sampling and Analysis Plan (SAP) presents the methods and procedures Arcadis U.S., Inc. (Arcadis) will use during field activities at the Grants Reclamation Project (GRP) located in Grants, New Mexico (site). Arcadis prepared this SAP on behalf of Homestake Mining Company of California (HMC). The field activities covered in this SAP include geophysical assessments, lithological assessments, the installation of additional groundwater monitoring wells, and soil and groundwater analyses that support this background investigation at the Site. Details of the Arcadis scope of work are provided below. This SAP is meant to cover only those objectives listed in **Section 1.1**.

The GRP is a former uranium mill located 5.5 miles north of Milan, Cibola County, New Mexico, as shown on **Figure 1**. Recent site activities have included groundwater and soil sampling of wells and boreholes in the background area north of the Site to better characterize constituent of concern (COC) distribution in alluvial materials and alluvial groundwater. Further work will be conducted to characterize the nature and distribution of the alluvial materials, their lithology, mineralogy, hydraulic conductivity, and deposition across the alluvial channel. This will include electrical resistivity tomography (ERT) and downhole geophysical logging, lithological assessments of four new borehole cores, collection and analysis of soil samples from two of the new borehole cores, and analysis of groundwater samples from the new wells.

1.1 Objectives

The specific objectives of this SAP are to:

- Develop site-specific data quality objectives (DQOs) (**Section 2**);
- Describe the field methods and locations for investigation activities, including geophysical assessments via ERT and downhole logging, lithological assessments of four new borehole cores, collection and analysis of soil samples from the borehole cores, installation and completion of four new wells, and analysis of groundwater samples from the new wells (**Section 3**);
- Summarize the laboratory analytical program (**Section 3**); and
- Specify field and laboratory quality assurance/quality control (QA/QC) procedures for collecting data that will satisfy the DQOs and are capable of withstanding critical and peer review (**Section 4**).

1.2 Distribution and Revision

Addenda, updates, or revisions to this SAP will be prepared if guidelines, procedures, regulatory documents, or Standard Operating Procedures (SOPs) are revised or when project objectives, scope, or activities change.

The May 2019 revision of this SAP incorporates updates after review by USEPA and NMED and after completion of the ERT survey. Borehole locations BK1, BK2, BK3 and BK4 have been identified and work planned for each of these locations is described herein.

1.3 Work Tasks

This SAP pertains to the following elements of the work plan:

SAMPLING AND ANALYSIS PLAN: 2019 BACKGROUND INVESTIGATION

- ERT survey, downhole geophysical survey of existing wells, borehole installation (at BK1, BK2, BK3, and BK4), downhole geophysical survey, and well installation activities (at BK1 and BK2);
- Analysis of soil (recovered from the boreholes (BK1, BK2, and BK3) and groundwater (sampled by HMC after the wells are completed), including the analytical methods to be used;
- Subsurface and above-grade utility location requirements;
- Permitting requirements; and
- Waste management and disposal requirements.

2 PROJECT DATA QUALITY OBJECTIVES

DQOs were developed in accordance with the United States Environmental Protection Agency's (USEPA's) 7-step DQO Process presented in Guidance on Systematic Planning Using the Data Quality Objectives Process, USEPA QA/G-4, EPA/240/B-06/001, February 2006 (USEPA 2006). As described in this guidance, the DQO process is used to develop performance and acceptance criteria (or DQOs) that clarify study objectives, define the appropriate type of data, and specify tolerable levels of potential decision errors that will be used as the basis for establishing the quality and quantity of data needed to support decisions. The DQO process identifies the problem, the goal of the study, the information inputs, the boundaries of the study, the analytical approach, the performance and acceptance criteria, and the plan for obtaining data, as follows:

<p>Step 1: State the Problem</p> <p>Stakeholder groups have requested a better understanding of site-specific background water quality standards and the occurrence of uranium in the alluvial system at the GRP. In 2016, the USEPA, with the assistance of the U.S. Geological Survey (USGS), initiated a reassessment of site background water quality standards and included well reconnaissance, geophysics, and sampling of groundwater via micropurge, volume purge, and passive sampling techniques. HMC engaged Arcadis to collect split samples with the USGS during the 2016 sampling events.</p> <p>Arcadis' interpretation of data collected during split sampling and a subsequent soil investigation is that groundwater uranium concentrations in near-upgradient alluvial wells are attributed to locally naturally occurring uranium in soils. Arcadis prepared a detailed report (Arcadis 2018a) that is included as an appendix in a white paper (Arcadis 2018b) documenting this conceptual site model (CSM). The white paper was provided to the USEPA and New Mexico Environment Department (NMED), and the findings were discussed in subsequent meetings with the USEPA, NMED, HMC, Nuclear Regulatory Commission, and Arcadis. In order to address technical inquiries from the USEPA and NMED relating to the CSM, a supplemental background investigation was deemed necessary.</p>
<p>Step 2: Identify the Goal of the Study</p> <p>The primary goal of the supplemental background investigation is to refine the CSM for natural uranium distribution and transport by identifying the lithological and hydraulic conductivity heterogeneity as well as the local variation in uranium concentrations across the alluvial channel upgradient (north) of the large tailing pile (LTP).</p>
<p>Step 3: Identify Information Inputs</p> <p>The data needed to accomplish the goals of the supplemental background investigation are as follows:</p> <ul style="list-style-type: none"> • Lithology and stratigraphy of the alluvial channel north of the LTP, including visualization of channel geometry and high-permeability zones containing coarse-grained materials; • In-situ alluvium concentrations of uranium, thorium, and potassium to 1) identify relationships between naturally occurring uranium and litho-stratigraphic conditions, mineralogy, and geochemical parameters, and 2) interpretation of the provenance of the alluvial sediments using the thorium-potassium ratios;

<ul style="list-style-type: none"> Mineralogical and geochemical data as well as uranium and other element concentrations from both fine-grained and coarse-grained sediments; and Temporal trends in geochemical data and uranium concentrations in groundwater associated with (i.e., separately screened across) fine-grained and coarse-grained sediments.
Step 4: Define the Boundaries of the Study
<p>Geophysical, lithological, and sampling activities to obtain the data needed to support the goals of the supplemental background investigation will include new boreholes and wells located along a cross-section across the alluvial channel as well as existing alluvial aquifer wells north of the LTP at the GRP.</p>
Step 5: Develop the Analytical Approach
<p>Geophysical assessments include an ERT assessment and downhole geophysical logging.</p> <ul style="list-style-type: none"> ERT assessment data will be used to inform the drilling phase of the program as well as to map the alluvial channel geometry and high-permeability zones. Downhole geophysical logging of existing and new boreholes/wells will provide a common set of detailed, quantitative, in-situ measurements to link interpretations between visual geologic descriptions, lithology of alluvial material surrounding existing monitoring wells where visual descriptions may be unavailable or of low detail, and the large-scale ERT cross-sections. <p>Lithological assessment and installation of two groundwater wells will be conducted at two different locations along the ERT transects.</p> <ul style="list-style-type: none"> Soil sampling during advancement of the boreholes will provide geochemical data from both fine-grained and coarse-grained sediments. The groundwater monitoring wells will be installed with short screen intervals separately screened across the fine-grained and coarse-grained sediments to assess the associated geochemical trends in groundwater. <p>The results will be used to refine the CSM.</p> <ul style="list-style-type: none"> Groundwater data reflecting that higher uranium concentrations are associated with the finer-grained sediments would indicate that uranium was naturally emplaced during fluvial deposition and is being released into groundwater by natural processes. Conversely, groundwater data reflecting that higher uranium concentrations are associated with the coarser-grained, high hydraulic conductivity sediments could suggest that uranium in groundwater may be present because of regional groundwater sources.
Step 6: Specify Performance or Acceptance Criteria
<p>Measurement performance criteria are specified in the Quality Assurance Project Plan (QAPP) for the GRP included as Appendix A of this SAP.</p>
Step 7: Develop the Plan for Obtaining Data
<p>This SAP presents the rationale and plan, including field and analytical methods, for obtaining geophysical, lithological, and soil and groundwater sampling data.</p>

3 INVESTIGATION ACTIVITIES AND METHODS

This section describes the field methods and locations for the following investigation activities: geophysical assessments via ERT and downhole logging (in existing and new wells), lithological assessments of four new borehole cores, collection and analysis of soil samples from two of the borehole cores, installation and completion of four new wells, and analysis of groundwater samples from the wells.

3.1 Geophysical Assessments - Electrical Resistivity Tomography and Borehole Logging Upgradient from the LTP

3.1.1 Electrical Resistivity Tomography Assessment

Arcadis will use an ERT assessment to map alluvial channel geometry and zones containing high-permeability coarse-grained materials. The ERT data will be used to inform the drilling phase of the program (see **Section 3.1.2**) to determine well positioning and well construction details, including the desired well screen interval.

Electrical resistivity is an intrinsic property of materials that varies widely in the subsurface and often correlates with lithology and geochemistry. For soils and rock, resistivity is a function of porosity, ionic content of the pore fluids (usually groundwater), and electrically conductive/reactive minerals such as pyrite and some clay minerals. By measuring the distribution of resistivity values in the subsurface, the presence and structure of geologic features can be inferred. For the Site, it is assumed that alluvial sediments composed of coarser-grained sand and gravels will display higher resistivity values relative to fine-grained silts and clay sediments.

3.1.1.1 ERT Field Data Collection

The geophysical resistivity tomography work will be performed prior to the installation of any additional boreholes and/or wells as information gained from the sections will be used to more effectively target the drilling assessment(s), based on the lithological interpretation. To the extent possible, existing borehole data will be used to interpret the ERT results, including recent data collected from boreholes DD-BK/DD2-BK as well as newly collected borehole geophysical data from existing wells.

Electrical resistivity data will be collected along two east-west transects that span the alluvial channel, where each transect is approximately 7,600 feet in length, as illustrated on **Figure 2**. A combined dipole-dipole and strong gradient array type will be used to collect ERT data. These combined arrays provide optimal horizontal and vertical sensitivity required to capture the complexities of the stratigraphic environment. A total of five overlapping ERT data sets will be collected along each 7,600-foot transect line. The location of the electrodes in each ERT transect will be mapped with a high-precision global positioning system (GPS) surveying unit.

The ERT geophysical survey instruments will include:

- Advanced Geosciences, Inc., Super Sting R8™ electrical resistivity meter (or equivalent) and switch boxes, specialized electrical resistivity cables with up to 112 individual electrodes with maximum spacing of 6 meters, and stainless-steel electrode stakes for making ground contact. The effective imaging depth of this configuration is approximately 150 feet below ground surface.

Before the electrical resistivity survey begins, the electrodes and cables undergo a contact resistance test, which tests the integrity of each electrode coupling and ensures that the electrical resistance between the electrode and the soil material is appropriate to produce quality resistivity measurements. Salt water will be added around the electrodes to improve contact resistance. Lowering of contact resistance improves the ability to inject current. Arcadis generally uses a cutoff of 20 kilohms (k Ω) for surface data. Higher values may indicate that limited current can be injected for that electrode pair. It is important to witness the contact resistances and record them manually to determine the quality of contact. Note that the Super Sting automatically records the contact resistance for later use, but it is not easily reviewed in the field. Contact resistance values can provide a basis for editing data associated with electrodes that are malfunctioning or in poor contact with the formation. The survey will not begin until an adequate contact resistance test is completed.

In addition, utilities within 30 feet of the resistivity transects will be marked on the ground, so that resistivity anomalies from utilities can be identified in the data collected. Metallic well casings tend to create an especially strong anomaly; therefore, layout of the resistivity transects will avoid well casings by at least 30 to 50 feet, if possible.

3.1.1.2 ERT Data Processing

Following field data collection, acquired ERT data sets will be transferred to a computer and processed to create modelled cross-sections that are prepared for geologic interpretation by an experienced geophysicist. The two-dimensional (2D) ERT data will be reduced and processed using the RES2DINV software program by Geotomo Software. Prior to data modelling, a number of pre-processing steps will be completed, including removal of data with voltage spikes, poor voltage decay, and low data quality readings in the raw field data.

Resistivity data will be processed using a damped least-squares or smooth model inversion method using a finite element mesh to generate a 2D model of resistivity versus depth. The primary objective of inversion is to reduce data misfits between field measurements and calculated data of a reconstructed model. New and existing borehole geophysical (induction conductivity) data will be used to constrain (*a priori*) the resistivity models.

Final graphical representations of the results will show areas in which data were removed to provide confidence that the final inverted image was produced with sufficient data coverage. Areas with inadequate data coverage will be designated as questionable for interpretation.

Final modelled ERT data will be presented as cross-sectional views of the subsurface that depict the distribution of electrical resistivity variations in subsurface materials along a single line of data collection.

3.1.2 Downhole Geophysical Logging

During the same mobilization as the drilling and logging performed at four new locations along the resistivity lines, additional downhole logging will be performed at a sampling of existing wells to gather a distribution of lithologic and chemical results in a variety of locations, upgradient and downgradient, west and east, as shown on **Figure 2**. Arcadis will conduct natural gamma ray (NGR), spectral gamma ray (SGR), and induction conductivity logging in a number of existing wells at the Site (R, P2, P4, 914, 920, 921, 922, W, and L), and only SGR in an additional five wells (DD, DD2, MV, ND, and Q). Additionally, NGR, SGR, and induction conductivity will be conducted in the newly installed boreholes, sited by the ERT results, cased with 2-inch Schedule 40 polyvinyl chloride (PVC) riser. SGR will be performed in two

modes, dynamic and static. This approach will result in data that will provide direct estimation of the potassium, uranium, and thorium concentrations in the alluvium. The dynamic SGR data will be used to select the static SGR logging locations, and in turn the static SGR will be used to inform the decisions on which samples to select for laboratory testing.

The totality of the geophysically logged locations will be used to:

- Augment the existing descriptive logs to provide improved, detailed lithology estimates for older, existing wells;
- Provide additional insight into the relationships between sediment types and uranium concentrations;
- Analyze the thorium and potassium data to further develop the concept regarding sediment provenance; and
- Guide the interpretations of the ERT cross-sections.

Logging Equipment

Arcadis will collect downhole geophysical logs using a portable Matrix system manufactured by the Mount Sopris Instrument Company in Golden, Colorado. This system is a digital, multi-channel system designed primarily for shallow environmental and engineering studies. The logging system consists of two primary components. The first component is the integrated logging control unit, which remains at the surface with the equipment operator, and the second component is the downhole-logging probe. The control unit is joined physically and electronically to the chosen downhole probe with a steel cable, approximately 600 feet in length, containing a single insulated signal wire. The steel cable is spooled on an integrated electric winch mechanism. The downhole position of the probe is measured to a precision of 0.01 foot with a digital odometer. The electrical signals transmitted by the downhole probe are passed from the winch to a signal processor within the logging unit. Therefore, the processed digital data collected includes the probe depth, speed, and probe-specific measurements of the borehole. The data are recorded in a portable computer for real-time viewing and storage for later analysis.

The proposed geophysical probes to be used include:

- 1) Electromagnetic (EM) conductivity probe
- 2) NGR probe
- 3) SGR probe.

The individual probes are further discussed in the subsections below.

EM Conductivity Probe

A Mount Sopris 2PIA-1000 EM conductivity probe will be used to provide information on the geologic strata beneath the Site. The operating principal for the EM probe is that the intensity of an induced secondary electromagnetic field is directly proportional to the electrical conductivity/resistivity of materials such as rocks, soils, and fresh water. In freshwater environments, clay-rich sediments/rocks generally have lower electrical resistivity than do sands because there are layers of unbound cations and anions adsorbed to the outer surfaces of the clay minerals. In the presence of electrical current, these cations

and anions are free to move and carry the electrical current. Similarly, fractured/weathered bedrock is much less resistive than competent bedrock. Data from this probe are output in electrical conductivity readings of milliSiemens per meter (mS/m).

The EM conductivity probe is relatively temperature sensitive, and site-specific calibration is necessary prior to logging. The manufacturer's calibration procedure will be performed prior to logging.

NGR Probe

A Mount Sopris 2PGA-1000 natural gamma probe will be used to provide information about the total level of natural gamma radiation emanating from subsurface stratigraphy. The 2PGA-1000 probe is a high sensitivity scintillometer that measures the gross NGR count. It has a relatively large sodium iodide crystal that optimizes the instrument sensitivity to the types of gamma rays generally encountered in clay minerals, as well as those from other naturally occurring radioactive elements and minerals. The data are presented in units of gamma ray counts per second (cps). Most NGR emissions are caused by minerals containing potassium, uranium, and/or thorium. While clay minerals (which contain the radioactive isotope potassium-40) are generally the most commonly observed natural gamma emitters, natural uranium may also be present on this Site. In contrast, geologic layers that contain little to no clay minerals (or other radioactive elements) emit very few gamma rays.

No field calibration is needed for the NGR probe. The manufacturer will provide a certificate of calibration for the specific probe used.

SGR Probe

A Mount Sopris 2SNA-1000-S spectral gamma probe will also be used to measure the natural gamma radiation emanating from the various geologic strata; however, this probe will split the total response into the various contributions from each of the major radio-isotopic sources. As such, this will allow the SGR log to differentiate between the NGR response of clay minerals (potassium-40), the uranium-radium series, and the thorium series, based on the energy level of each gamma ray encountered. Similar to the NGR probe, the 2SNA-1000-S also uses a high sensitivity scintillometer to measure the gamma ray count, and, once the counts have been separated into the various radio-isotopic components, they are presented in units of cps.

No field calibration is needed for the spectral gamma probe. The manufacturer will provide a certificate of calibration for the specific probe used.

Data Collection Procedures

Downhole logs from the three probes will be collected in each of the four boreholes, which will be cased in 2-inch solid PVC risers. The three logs per borehole will be collected in dynamic mode, at a rate appropriate for each probe per manufacturer's guidance. Additionally, static data will be collected from the SGR probe at key depth intervals selected from the dynamic data set for a time range of 10 to 15 minutes. This approach will result in data that will provide direct estimation of the uranium concentration in the alluvium. The static SGR will be used to decide which samples to select for laboratory testing.

During geophysical logging, Arcadis plans to document the activities conducted at each well, including at a minimum:

- Names of each personnel present
- Weather conditions
- Date and time of measurements
- Well details, including ID, diameter, total depth, screened interval, and static depth to water
- Tools being run and tool condition
- Tool calibration
- Logging speeds
- Depths evaluated
- Reproducibility of data acquisition
- Preliminary results (e.g., casing conditions)
- Decontamination procedures.

Observations of geophysical logging will be recorded on the geophysical logging observation form provided in **Appendix B**. Additionally, a field notebook will be maintained in accordance with the SOP for Field Log Book Entries (**Appendix C**). Arcadis personnel will also take representative photographs to document geophysical logging activities.

Data Analysis Procedures

The data collected from each of the logging probes will produce an integral data file developed specifically for importation into a data analysis and plotting program called WellCAD Version 5.2.

3.2 Lithological Assessment and Installation of Additional Wells

Arcadis will install four groundwater monitoring wells as part of this phase of the background study, at locations BK1 and BK2. Installation of four boreholes/groundwater monitoring wells will enable targeting of both coarse- and fine-grained sediments at the two locations selected for assessment along the geophysical resistivity lines. Soil sampling during advancement of the boreholes will provide geochemical data from both fine-grained and coarse-grained sediments. The groundwater monitoring wells will be installed with short screen intervals separately screened across the fine-grained and coarse-grained sediments to assess the associated geochemical trends in groundwater. The results will be used to assess the CSM for natural uranium placement and transport.

The lithological assessment and monitoring well installation program will consist of the following:

- Borehole drilling, lithological assessment, and sampling
- Downhole geophysical assessment
- First groundwater monitoring well installation (screened across coarse sediments)

- Second groundwater monitoring well installation (screened across fine sediments).

3.2.1 Drilling, Lithological Assessment, and Soil Sampling

Two boreholes will be drilled initially with locations (BK1 and BK2) based on the results of the ERT survey (see **Section 3.1.1**). Initial boreholes at each of two locations will be advanced through alluvial materials and 5 feet into bedrock. Bedrock is anticipated at a depth of approximately 95 to 105 feet, based on previous drilling. Core will be recovered for the entire borehole length, lithologically logged, and sampled for analysis of metals content, mineralogy, and leachability.

A geologist will continuously observe all drilling operations, and representative samples of the drill cuttings will be collected and logged at regular intervals during drilling in accordance with ASTM International (ASTM) Designation D2488. Lithologic descriptions will include soil type, color, grade, sorting, matrix, accessory minerals, hardness, and an estimation of moisture content. Observations of the drilling progress will also be captured and logged.

Based on the lithological assessment of the first two boreholes, two additional boreholes will be drilled for fine sediment wells. These boreholes will not necessarily be drilled to bedrock but will instead be drilled only to the depth of the targeted fine sediment, which is anticipated at approximately 60 to 70 feet below ground surface.

Soil sampling will be conducted as diagrammed in **Tables 1 and 2**. Sampling will be completed in a discretionary manner, targeting varying lithologies. During soil sampling, Arcadis plans to record, at a minimum, the following information:

- Name of each person present
- Sample dates and times
- Weather conditions
- Equipment and QA/QC procedures
- Sample preparation and field storage methods.

A field notebook will be maintained in accordance with the SOP for Field Log Book Entries (**Appendix C**). Arcadis personnel will also take photographs to document drilling and soil sampling activities.

The following analyses will be performed on soil samples collected from the first two boreholes, as well as borehole BK3 (**Table 1**):

- Paste pH, and oxidation-reduction potential (ORP) on soil
- Total metal and radionuclide content by USEPA Method 3050B (hydrochloric/nitric acid digestion) and USEPA Method 6020B (inductively coupled plasma mass spectrometry) – provides the concentration of “environmentally accessible” major and trace elements; up to 20 samples will be obtained for this analysis, with 10 samples taken from each initial borehole, targeting various lithologies. One additional sample will be submitted as a field duplicate, for a total of 21 samples.
 - Major elements that will be analyzed include aluminum, calcium, magnesium, potassium, sodium, silicon (often reported as silica), iron, and manganese. Trace elements and radionuclides include

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molybdenum, selenium, uranium, and vanadium. This set of analytes is heretofore referred to as the “elemental suite.”

- Analysis of total metals and radionuclides in density fractionated splits by USEPA Method 3050 with USEPA Method 6020B – provides an understanding of the association of uranium and other elements with specific mineral fractions, based on particle density. This analysis will be performed on 10 gravity fractionated splits and analyzed for the elemental suite.
- Selective Sequential Extraction (SSE) to evaluate the mineralogy that contains elements of interest in the following mineralogical fractions: water soluble, exchangeable, carbonate bound, oxide bound, organic bound, and recalcitrant (discussed further below) – up to 10 samples will be submitted for this analysis. Sample selection will be based on the initial results of the total metals analysis (one duplicate will be included in these 10 samples). The samples will be analyzed for the elemental suite, as well as sulfate, carbonate, and phosphate on the leachate from Step 1 (water soluble) and sulfate and phosphate on Step 2 (adsorbed) Note that the draft plan included a second step that has been changed from an exchangeable fraction that would include a magnesium chloride extraction to an alkaline leach solution as was used in the DD-BK and DD2-BK samples in 2018. This change allows data to be compared to other work completed and ongoing on alluvial sediment samples on-site, and it allows us to compare leachate from step 2 to SPLP leachate from the 2018 DD-BK/DD2-BK work. This change also eliminates the concern about whether calcium or magnesium is a better competitive displacer for uranium in the sediment samples; an exchangeable step may be less relevant to understanding uranium lability in sediments, and it is important to incorporate an alkaline leach step given the alkalinity of groundwater in the area.
- Total organic carbon and total sulfur content using the LECO induction furnace method on a subset of samples that show the highest uranium concentrations (up to five samples) – provides the association of uranium with organic carbon and sulfur.
- Light-microscopy (petrographic microscopy) to evaluate mineralogical characteristics in five samples.
- X-ray diffraction to determine major mineralogical content in five samples.
- Stable sulfur isotopes as analyzed by Isotope Tracer Technologies (IT2) Laboratories, Waterloo, Ontario, Canada – this will be performed on five samples. Possible pre-processing may be conducted to target sulfides in the samples through the oxidation of the sample with bromine.
- Electron/x-ray microscopy/spectroscopy (discussed below).

A summary of the soil analyses is provided below in **Exhibit 1**. A detailed summary of the sampling program, including laboratories chosen for each analysis, is provided in **Table 2**. Preservation requirements and method holding times are included in **Table 3**.

Exhibit 1. Summary of soil analyses to be performed on three new boreholes at the GRP

Analysis	Number of analyses ¹
Total metals, USEPA Method 3050B/6020 ²	10 per borehole (30 total)
Selective sequential extraction	15 total

Analysis	Number of analyses ¹
Total organic carbon and total sulfur content, LECO induction furnace ²	15 total
Petrographic microscopy	8 total
XRD	8 total
Soil sulfur isotopes	8 total
QEMSCAN ³	2 total
¹ Analysis of up to the total number of samples shown may be conducted. ² Sampling will include one duplicate analysis for a total of 21 samples. ³ Analytical techniques are being identified that can detect uranium at the low concentrations that occur in these samples; a different type of analysis may be substituted for QEMSCAN if it is determined to be more appropriate for this task.	

Selective Sequential Extraction

Ten samples will be subjected to SSE; the samples selected for this analysis will be based on the results of the total metals analysis, combined with the lithological evaluation, such that samples that contain uranium at various concentrations and across a range of lithologies (from sands to fine silts/clays) are selected. The SSE method uses chemical reagents that selectively dissolve individual phases or mineral forms of the target element under investigation, in this case uranium. The reagents range in chemical strength and are progressively stronger in terms of their ability to dissolve mineral phases. The results of this analysis will provide an indication of the leachability of each element based on the phase within which it predominantly resides (e.g., if 85 percent of the total uranium is found to be liberated in the water soluble fraction, then it is likely that uranium present in the sample is readily released into groundwater).

Extraction chemistries will proceed based on the SSE protocol outlined in Tessier et al. (1979) and summarized in **Table 4**. The details of the extraction procedure will be provided to the laboratory that will perform this work (ACZ Laboratories in Steamboat Springs, Colorado). A 2- to 5-gram sample of soil will be used, dried to determine the dry weight, and ground prior to the SSE. The steps in the sequential extraction and reagents are described below:

Extraction Step 1: Water Soluble

This step will extract uranium and other elements that are readily dissolved in water. Distilled water will be added to soil and shaken for 1 hour and then centrifuged at 12,000x gravity force for 30 minutes, with the supernatant recovered and analyzed for the elemental suite as well as sulfate, phosphate, and carbonate.

Extraction Step 2: Adsorbed

This step will extract uranium and other elements that are displaced by bicarbonate/carbonate, simulating interaction of the soil with groundwater chemical conditions relevant to the alluvial aquifer (specifically the presence of alkalinity that can enhance uranium solubility). A reagent consisting of 0.014M sodium bicarbonate and 0.003 M sodium carbonate will be added to soil and shaken for 1 hour, followed by rinsing with deionized water. The supernatant will be analyzed for the elemental suite as well as sulfate and phosphate.

Extraction Step 3: Carbonate Bound

This step will extract elements that are associated with carbonate minerals; dilute sodium acetate will be used (1 molar, adjusted to pH 5 with acetic acid). The sample will be shaken for 2.5 hours with venting to liberate any evolved gases, centrifuged, and the supernatant will be analyzed for the elemental suite.

Extraction Step 4: Oxide Bound

This step will extract elements that are associated with amorphous and crystalline iron- and manganese-oxides. Dilute hydroxylamine hydrochloride (0.04 molar) in 25 percent by volume acetic acid will be used, with the sample heated at 96 ± 3 degrees Celsius ($^{\circ}\text{C}$) for 6 hours. At the end of the digestion, the sample will be centrifuged and the supernatant will be analyzed for the elemental suite.

Extraction Step 5: Organic Bound

This step will extract elements that are associated with organic carbon. The extraction reagent will consist of ammonium acetate (3.2 molar) adjusted to pH 2 with nitric acid, and the sample will be heated at $85 \pm 3^{\circ}\text{C}$ for 2 hours. After heating, concentrated hydrogen peroxide will be added (adjusted to pH 2 with nitric acid) followed by heating at $85 \pm 3^{\circ}\text{C}$ for 3 hours. The supernatant will be recovered and analyzed for the elemental suite.

Extraction Step 6: Residual

The final step in the SSE will digest any remaining material – this step will dissolve the “recalcitrant” or residual elements that are tightly bound to the soil and virtually insoluble. USEPA Method 3052 will be used for this extraction step; this employs concentrated nitric, hydrochloric, and hydrofluoric acids. The digested material will be analyzed for the elemental suite.

As a data evaluation/quality control measure, the concentration of the elements in each extraction step (prior to the residual [3052] extraction step) will be summed and compared to the results of the 3050B digestion, performed separately on the samples, in order to develop a mass balance that will inform how well the recovery from each individual step matches with the total concentration of each element. The data will be reported as the concentration of each element extracted in each step, as well as the fraction of each element associated with each targeted phase.

Scanning Electron Microscopy (SEM)

QEMSCAN will be used to analyze two samples selected based on the total metals content and lithologic description, with preference given to those samples that contain the highest concentrations of uranium. This method will be used instead of conventional SEM because of its ability to automate SEM data collection and improved (better resolution) energy dispersive x-ray spectroscopy (EDS) data. Soil samples will be embedded in epoxy and polished so that the surface is of optimal (smooth) roughness for the analysis. Automated mapping of the elemental composition of the sample will be performed with a focus of the analysis on locating uranium, and its elemental association. In addition, the size of the uranium-bearing particles will be identified along with the general morphology of the particles. Due to the possibility that the uranium concentrations are too low to be detected via EDS, additional sample analysis techniques are currently being investigated. If it is determined that a different technique would yield better spatial data related to uranium distribution in these samples, QEMSCAN may be replaced with the more

advantageous method. In addition, sample preparation methods based upon particle size fractionation and mineral density are being evaluated for their utility in enhancing the success of QEMSCAN analysis.

3.2.2 Downhole Geophysical Assessment

During the same mobilization as the borehole drilling and logging, as described above, downhole geophysical assessments will be conducted on all of the boreholes (BK1 through BK4). Due to potential interactions between the downhole geophysical tools and well completion materials (e.g., bentonite), downhole geophysical assessments will be conducted at two time periods on each initial borehole (BK1 and BK2):

- When the first borehole has reached its total depth and the drill casing is still in place prior to well installation, logging for natural gamma/spectral gamma will be conducted. This will prevent interference by well materials that will be present after well construction (such as bentonite) on the gamma data.
- After installation of the well, induction conductivity will be conducted.

Downhole logging will be performed as described in **Section 3.1.2** of this SAP.

3.2.3 Well Installation

Four wells will be installed, two at each of the two initial borehole locations (BK1 and BK2), as follows:

- **First Well Installation at Each Location (Coarse Sediments):** This groundwater well screen interval will be placed to target coarse, higher-permeability sediments. The screen placement will be based on the surface geophysical resistivity assessment and refined by core lithological logging. The well will be installed with a 2-inch Schedule 40 PVC casing that extends into the bedrock to enable the downhole geophysics to be conducted, but it will have a short screen interval (5 to 10 feet in length) for targeted groundwater collection. The screen section will be hydraulically isolated by placement of bentonite chips both above and below the screen interval.
- **Second Well Installation (Fine Sediments):** The construction of this groundwater well will be based on the results of the downhole geophysical assessment, with the screen interval targeting fine-grained sediments.

The newly installed wells will be developed no sooner than 48 hours after installation to allow adequate time for the well seals to cure. The wells will be developed by surging, bailing, and pumping to remove fine sediment introduced during drilling and/or well construction. During well development, the volume of water removed and field parameters will be measured, including pH, electrical conductivity, turbidity, oxidation-reduction potential, dissolved oxygen, and temperature. Development will continue until the turbidity is significantly reduced, targeting readings less than five nephelometric turbidity units and parameters have stabilized (less than 10 percent variation in readings).

Anticipated well construction details and well installation and development procedures are discussed in the Work Plan: 2019 Background Investigation at the GRP.

3.3 Groundwater Sampling

Groundwater well sampling will be conducted on the newly installed wells by HMC staff at least 48 hours after well development.

3.3.1 Water Level Measurement

Static water level measurements will be collected using a water level indicator prior to conducting purging and sampling activities. Static water levels will be measured relative to surveyed datum (i.e., top of well casing) to the nearest 0.01 foot and recorded in the appropriate field logbook or groundwater sampling form. Field staff will collect water level measurements in accordance with the SOP for Water Level Measurement (**Appendix C**).

3.3.2 Field Parameter Measurement

Field parameters (temperature, pH, specific conductance, dissolved oxygen, turbidity, and oxidation-reduction potential) will be measured during purging and immediately before sample collection during volume purge groundwater sampling. Field parameters will be measured in accordance with HMC's sampling protocol. The type of electrodes used for the field parameter measurements will be recorded in the field log book. Ferrous iron will be determined in the field using Hach test kits.

3.3.3 Groundwater Analyses

Groundwater will be collected, preserved as appropriate, and sent to Energy Laboratories, Inc., unless otherwise noted. Samples will be analyzed for:

- Total metals via USEPA Method 6020 for aluminum, calcium, iron, potassium, magnesium, manganese, molybdenum, sodium, selenium, uranium, and vanadium; sample will be unfiltered and preserved with nitric acid.
- Dissolved metals via USEPA Method 6020 for aluminum, calcium, iron, potassium, magnesium, manganese, molybdenum, sodium, selenium, uranium, and vanadium; sample will be field filtered to 0.45 micron and preserved with nitric acid.
- Alkalinity via Standard Method (SM) 2320
- Major anions, including sulfate and chloride (USEPA Method 300.0), and nitrate/nitrite (SM 4500)
- Uranium isotopes (U-234, U-235, and U-238)
- Sulfur stable isotopes through IT2 Laboratories.
- Total organic carbon and dissolved organic carbon (after filtration through a 0.45 µm filter) by SM5310C
- Phosphate-phosphorus by USEPA Method 365.1

4 QUALITY ASSURANCE AND QUALITY CONTROL

4.1 Field Documentation and Sample Labeling

Daily activities will be recorded in a dedicated field notebook. Field books will be completed in accordance with the procedures outlined in the SOP for Field Log Book Entries (**Appendix C**). Sampling logs and collection forms will be used to document site and sample data as detailed above.

Each analytical sample will be given a unique alphanumeric identifier as defined in **Table 5**.

4.2 Field Quality Assurance and Quality Control

Sample collection and handling and laboratory analyses will be conducted in accordance with the QAPP (**Appendix A**). Field QA/QC is dependent on proper equipment calibration, decontamination, and care by field workers to adhere to SOPs and field protocols. Critical components of the field QA/QC process include documenting field activities, cross-checking sample labels, chain-of-custody forms, and field documents, and completing daily activity logs. Additional checks on field QA/QC include collection of field duplicates, equipment blank samples (where appropriate), field blank samples (where appropriate), and matrix spike (MS)/matrix spike duplicate (MSD) samples, where appropriate. **Table 6** provides the frequency at which field QA/QC samples will be collected.

- Field duplicate samples are collected to measure the sampling and analytical variability associated with the sample results. Duplicate samples are usually collected simultaneously with or immediately after the corresponding original samples have been collected. The same sampling protocol is used to collect the original sample and the field duplicate sample. The field duplicate is analyzed for the same suite of analytical parameters as the original sample. Field duplicates will be collected at a rate of one per 20 samples, in accordance with the Contract Laboratory Program National Functional Guidelines for Inorganic Review (USEPA 2014).
- Equipment blanks will not be collected for soil samples because the soil will be accessed directly using single-use, sterile, disposable scoops and placed directly into a laboratory-supplied sample container.
- An MS/MSD is a double-volume sample used by the laboratory to evaluate whether matrix effects are interfering with sample analyses and, therefore, compromising the accuracy or precision of those analyses. MS/MSD samples will be collected at a frequency of one per 20 samples (USEPA 2014). Additional sample containers for MS/MSD sample analyses will be labeled using the same sample identification as the parent sample.

Field QA/QC sample descriptions, collection procedures, and collection frequencies are summarized in **Table 6**.

4.3 Investigation-Derived Waste

It is anticipated that three main types of investigation-derived waste (IDW) may be created as a result of field activities: drilling boreholes, pump/purge water generated as a result of groundwater well development, and routine disposal of personal protective equipment (PPE). IDW drill cuttings generated

during borehole drilling and IDW water from well pump/purging will be disposed of on site as directed by HMC. PPE will be disposed of on site as municipal solid waste.

4.4 Additional Sampling Events

If HMC intends to conduct any additional sampling events following the activities described in this SAP, Arcadis will prepare a technical addendum to this SAP that outlines the locations and analyses that will be part of the additional sampling events.

5 HEALTH AND SAFETY

HMC and Arcadis place the highest priority on the safe and environmentally responsible conduct of the work and follow the “every person going home safe and healthy every day” mentality. As such, HMC has outlined specific health and safety compliance guidance for all site workers. Site activities will follow all HMC health and safety compliance requirements including, but not limited to:

- HMC Grants Reclamation Project specific contractor requirements
- As Low As Reasonably Achievable (ALARA) training as required by HMC prior to site entry
- Radiation Awareness training in accordance with HMC and Arcadis standards.

Arcadis has created a site-specific Health and Safety Plan (HASP) to outline safety expectations and provide guidance for safe work practices for all field activities. The HASP outlines a site-specific hazard analysis and mitigation, monitoring plan, and training requirements that follow both HMC and Arcadis safety policies. The HASP is required reading for personnel conducting field activities at the Site.

Prior to commencing work each day, the Daily Health and Safety Plan Tailgate Meeting Form must be completed and maintained in the project files and/or electronic directory. The date and general content of a daily morning health and safety meeting will be recorded on Daily Logs.

6 REFERENCES

- Arcadis. 2018a. Grants Reclamation Project, Site Specific Health and Safety Plan. January.
- Arcadis. 2018b. Sampling and Analysis Plan Addendum to the 2016 Sampling and Analysis Plan: Supplemental Groundwater Quality Background Assessment.
- Tessier, A., P.G.C. Campbell, and M. Bisson. 1979. Sequential extraction procedure for the speciation of particulate trace metals. *Analytical Chemistry*. 51:844-851.
- USEPA. 2006. Guidance on Systematic Planning Using the Data Quality Objectives Process, EPA QA/G-4. EPA-240-B-06-001.
- USEPA. 2014. National Functional Guidelines for Inorganic Superfund Data Review. EPA-540-R-013-001. August.

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SAP TABLES



Table 1
Soil Analysis Goals
2019 Background Investigation
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Analyte	Method	Supporting Detail and Analysis Goal
Total metals in soil ^a (environmentally accessible)	USEPA 3050B with 6020Bb	Analysis of total metals in soil is necessary to provide an understanding of the geochemical behavior of constituents of concern in the alluvial aquifer and alluvial sediments. This analysis will provide the concentration of environmentally accessible major and trace elements.
Selective Sequential Extraction ^b	Custom per Tessier et al. 1979	Selective sequential extraction uses chemical reagents that selectively dissolve individual phases or mineral forms of the target element under investigation, in this case uranium. The reagents range in chemical strength and are progressively stronger in terms of their ability to dissolve mineral phases. The results of this analysis will provide an indication of the leachability of each element based on the phase within which it predominantly resides.
Total Organic Carbon	LECO Induction Furnace	This analysis will provide an understanding of the association of uranium with organic carbon and will be performed on a subset of samples that show the highest uranium concentrations. Prior work on soils has shown the presence of particulate organic carbon.
Total Sulfur Content	LECO Induction Furnace	This analysis will provide an understanding of the association of uranium with sulfur and will be performed on a subset of samples that show the highest uranium concentrations. Prior work on soils has shown the presence of sulfide minerals.
Precise mineralogy	Petrographic microscopy	Petrographic analysis via light and polarized light microscopy has the capability to produce a definitive mineralogic assessment of alluvial aquifer sediments, including identification of small mineral grains, which cannot be resolved through x-ray diffraction.
Bulk mineralogy	XRD - scan and search	X-ray diffraction analysis can generate positive identification of a wide variety of mineral constituents in a sample. In contrast to petrographic and SEM-EDX analyses, which require manual microscopic exploration and targeted identification, XRD is most valuable as a bulk assessment of mineralogy and yields essential data about mineralogic variability throughout the alluvial aquifer. Based on previous characterization of uranium in the San Mateo Valley alluvial system, the majority of the uranium is expected to be encountered in coarse-grained sands and possibly silts; thus, the "scan and search" XRD method is expected to be sufficient. However, if samples that show the highest uranium are predominantly clay, a directed clay XRD analysis must be used instead.
Sulfur stable isotopes in soil ^c	Stable sulfur isotopes as analyzed by Isotope Tracer Technologies (IT ²), Waterloo, Ontario, Canada	Sulfur stable isotopes related to solid sulfates and sulfides and to sulfate in groundwater give an indication of the origin of sediments and groundwater that is difficult to achieve through other methods. Sulfur that is more highly depleted in the heavier sulfur isotopes (e.g., sulfur-34) has most likely been through the microbial sulfate reduction process. This process can only occur when a system is significantly reducing and, as a result, represents an environment where uranium reduction, precipitation, and concentration could occur.
Mineralogy and elemental composition	QEMSCAN	QEMSCAN is a rastering scanning electron microscope technique with four Energy Dispersive Spectrometers that uses proprietary software to map the mineral distribution across a sample surface. QEMSCAN can identify areas in a sample that contain concentrated uranium and on which higher resolution analysis can be conducted. QEMSCAN increases the probability of encountering uranium in environmental samples over traditional non-rastering scanning electron microscopy.

Notes:

^a Will be analyzed for aluminum, calcium, iron, magnesium, manganese, molybdenum, potassium, selenium, sodium, sulfur, uranium, and vanadium.

^b Will be analyzed for aluminum, calcium, iron, magnesium, manganese, molybdenum, potassium, selenium, sodium, sulfur, uranium, and vanadium plus silicon (often reported as silica).

^c Conducted at Isotope Tracer Technologies, Inc. (IT²)

USEPA = United States Environmental Protection Agency

QEMSCAN = Quantitative Evaluation of Materials by SCANning electron microscopy

SEM = scanning electron microscopy

XRD = x-ray diffraction

Laboratory	Energy Laboratories, Incorporated (ELI)			Huffman-Hazen Labs	ACZ Laboratories	DCM through ELI ^{c,d}	IT ^f
Analysis	Environmentally accessible metals in sediment ^b	Total Organic Carbon	Total sulfur content	Mineralogy and elemental composition	Total metals by mineralogical fraction ^b	Precise mineralogy	Stable sulfur isotopes
Method ^a	USEPA 3050B with 6020B ^b	LECO Induction Furnace	LECO Induction Furnace	QEMSCAN ^e	Selective Sequential Extraction based on Tessier et al. 1979 (Table 4) with 6020B ^b	Petrographic analysis	Stable sulfur isotopes as analyzed by isotope Tracer Technologies (IT ^f), Waterloo, Ontario, Canada
Number of samples	Up to 10 samples each initial boring	Up to 15 samples	Up to 15 samples	Up to 2 samples	Up to 30 samples	Up to 3 samples	Up to 8 samples
Sample container per each sample	1 4-ounce glass jar				1 4-ounce glass jar	1 small whirl-top or zip-top plastic bag	1 4-ounce glass jar
Well/Location ID	Samples collected in the field per borehole						
BK1-C	10 samples	Up to 5 samples	Up to 5 samples	1 sample	Up to 10 samples	Up to 3 samples	Up to 3 samples
BK2-C	10 samples	Up to 5 samples	Up to 5 samples	--	Up to 10 samples	Up to 2 samples	Up to 2 samples
BK1-F	--	--	--	--	--	--	--
BK2-F	--	--	--	--	--	--	--
BK3	10 samples	Up to 5 samples	Up to 5 samples	1 sample			
DUP	One sample	One sample	One sample	--	Up to 10 samples	Up to 3 samples	Up to 3 samples
MS/MSD	One sample	One sample	One sample	--	--	--	--

Notes:

^a Specific methods are subject to change based on the laboratory capabilities at the time of sample submittal.

^b Will be analyzed for aluminum, calcium, iron, magnesium, manganese, molybdenum, potassium, selenium, silicon, sodium, uranium, and vanadium.

^c DCM will be subcontracted through ELI.

^d Microscopy samples will be collected, homogenized in their sample container, packaged in the field, and sent to ELI; all microscopy samples will be retained by ELI until Arcadis reviews data from the total metals analysis. Arcadis will subsequently select up to 5 microscopy samples to be shipped by ELI to DCM for analysis.

^e Analytical techniques are being identified that can detect uranium at the low concentrations that occur in these samples; a different type of analysis may be substituted for QEMSCAN if it is determined to be more appropriate for this task.

^f Ten splits from the density fractional separation of five field samples conducted by Hazen Laboratories will be sent to ELI for analysis of aluminium, calcium, iron, magnesium, manganese, molybdenum, potassium, selenium, silicon, sodium, uranium, and vanadium.

-- = no sample to be collected

ACZ = ACZ Laboratories in Steamboat Springs, Colorado

DCM = DCM Science Laboratory, Incorporated in Wheat Ridge, Colorado

DUP = duplicate measurement/sample

ELI = Energy Laboratories, Incorporated in Casper, Wyoming

BK1-C = borehole installed at location 1 that will be screened in coarse sediments when converted to a well

BK1-F = borehole installed at location 1 that will be screened in fine sediments when converted to a well

BK2-C = borehole installed at location 2 that will be screened in coarse sediments when converted to a well

BK2-F = borehole installed at location 2 that will be screened in fine sediments when converted to a well

MS/MSD = matrix spike/matrix spike duplicate; MS/MSD samples do not require a separate sample ID; samples intended for MS/MSD analysis should be indicated in the comment section of the Chain of Custody form.

QEMSCAN = Quantitative Evaluation of Materials by SCANning electron microscopy

USEPA = United States Environmental Protection Agency

XRD = x-ray diffraction

Table 3
Analytical Methods, Preservation, and Holding Times
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Laboratory Measurement or Task	Matrix	Preservation	Sample Volume or Containers	Holding Times	Analytical Method ^a	Special Handling
Energy Laboratories, Inc.						
pH and ORP on soil	solid	4 ± 2°C	One 4-Ounce glass jar	20 days	ASA10-3 (pH) and A2590BM (ORP)	--
Environmentally accesible metals in solids ^b	solid	4 ± 2°C	One 4-Ounce glass jar	180 days	EPA 3050B/6020B	--
Total metals by particle size ^b	solid	4 ± 2°C	Samples as prepared by Huffman Hazen Laboratories (HHL)	179 days from the date of collection	EPA 3050B/6020B	Samples sent from HHL to ELI
Total Organic Carbon	solid	4 ± 2°C	One 1-Quart plastic zip-top bag	30 days	LECO Induction Furnace	--
Total sulfur	solid	4 ± 2°C		30 days	LECO Induction Furnace	--
Total metals ^b	water	HNO ₃ to pH<2; 4 ± 2°C	250 mL plastic, nonfiltered	6 months	EPA 6020	--
Dissolved metals ^b	water	HNO ₃ to pH<2; 4 ± 2°C	250 mL plastic, filtered	6 months	EPA 6020	--
Alkalinity as CaCO ₃	water	4 ± 2°C	One 1-Liter plastic, nonfiltered	14 days	SM 2320B	--
Major Anions ^c	water	4 ± 2°C	One 1-Liter plastic, nonfiltered	28 days	EPA 300.0	--
Nitrate as N	water	H ₂ SO ₄ to pH <2; 4 ± 2°C	250 mL plastic, nonfiltered	28 days	SM 4500	--
Ammonia as N	water	H ₂ SO ₄ to pH <2; 4 ± 2°C	250 mL plastic, nonfiltered	28 days	SM 4500	--
Uranium-234, -235,-238	water	HNO ₃ to pH<2; 4 ± 2°C	Two 1-Liter plastic, nonfiltered	180 days	EPA 908.0	--
IT ² Laboratories						
Sulfur stable isotopes	water	none	One 1-Liter plastic, nonfiltered	none specified	Stable sulfur isotopes as analyzed by Isotope Tracer Technologies (IT2), Waterloo, Ontario, Canada	Provide sulfate and chloride results for parent samples when available, needed before analysis is performed. Volume must contain 10 mg sulfate, high chloride samples must contain 20 mg sulfate.
Sulfur stable isotopes	solid	none	200 grams	none specified		--
Huffman Hazen Laboratories (HHL)						
Mineralogical identification via QEMSCAN	solid	none		none specified	QEMSCAN	--
DCM Laboratory, Inc.						
Prepare thin sections	solid	none	1 small whirl-top or zip-top plastic bag for all analyses	none specified	DCM SOP	--
Petrographic analysis	solid	none		none specified	DCM SOP	--
X-ray diffraction	solid	none		none specified	DCM SOP	--
ACZ Laboratories, Inc.						
Selective sequential extraction (SSE)	solid	none	40 grams of material in whirl-top or zip-top plastic bag	none specified	SSE (Table 4), EPA 3050B/6020B	--

Notes:

-- = not applicable/required

^a Specific methods are subject to change based on the laboratory capabilities at the time of sample submittal

^b Will be analyzed for aluminum, calcium, iron, magnesium, manganese, molybdenum, potassium, selenium, silicon, sodium, uranium, vanadium

^c Must include chloride, fluoride, sulfate

< = less than

°C = degrees Celsius

ACZ = ACZ Laboratories, Inc.

ASTM = ASTM International

CaCO₃ = calcium carbonate

DCM = DCM Science Laboratory, Inc.

EPA = United States Environmental Protection Agency

HNO₃ = nitric acid

H₂SO₄ = sulfuric acid

H₃PO₄ = phosphoric acid

mL = milliliter

QEMSCAN = Quantitative Evaluation of Materials by SCANNing electron microscopy

SEM-EDS = scanning electron microscopy with energy dispersive x-ray spectroscopy

SM = Standard Method

SOP = standard operating procedure

SSE = selective sequential extraction

XRD = x-ray diffraction

Table 4
Selective Sequential Extraction Protocol
2019 Background Investigation
Grants Reclamation Project

Extraction Step	Description	Reagent	Procedure
I	Water Soluble	Distilled water	<ol style="list-style-type: none"> 1. Prepare sample by drying at 105 °C and grinding in agate mortar. 2. Weigh 2.0 grams of soil into 50 mL centrifuge tube. 3. Add 30 mL deionized H₂O. 4. Shake for 1 hour. 5. Centrifuge at 12,000 g for 30 minutes. 6. Pipette supernatant into plastic syringe and filter through 0.45 µm pore-size syringe filter. 7. Analyze supernatant for U, V, Se, Mo, Ca, Mg, Na, Al, Fe, Mn, Si, sulfate, carbonate, phosphate
II	Adsorbed	0.0144M NaHCO ₃ / 0.0028 M Na ₂ CO ₃	<ol style="list-style-type: none"> 1. Add 16 mL of 0.0144 M NaHCO₃ / 0.0028 M Na₂CO₃ solution. 2. Shake for 1 hr. 3. Centrifuge @ 12,000 g for 30 minutes. 4. Pipette supernatant into plastic syringe and filter through 0.45 µm pore-size syringe filter. 5. Analyze supernatant for U, V, Se, Mo, Ca, Mg, Na, K, Al, Fe, Mn, Si, sulfate, phosphate 6. Add 16 mL deionized H₂O into centrifuge tube containing the solid sample and hand shake for 1 minute. 7. Centrifuge @ 12,000 g for 30 minutes. 8. Pipette and discard supernatant.
III	Carbonate Bound	1 M NaOAc (pH = 5.0)	<ol style="list-style-type: none"> 1. Add 16 mL of 1 M NaOAc (adjusted to pH = 5 with HOAc). 2. Shake for 2.5 hour. 3. Repeat steps 3 through 8 in Extraction Step II.
IV	Oxide Bound	0.04 M NH ₂ OH·HCl in 25% (v/v) HOAc	<ol style="list-style-type: none"> 1. Add 40 mL of 0.04 M NH₂OH·HCl in 25% (v/v) HOAc (pH ≈ 2). 2. Hand shake for 1 minute. 3. Place in oven at 96 ± 3 °C for 6 hours. Hand shake every 1 hour. 4. After 6 hours, remove from oven and hand shake. 5. Repeat steps 3 through 8 in Extraction Step II.
V	Organic Bound	0.02 M HNO ₃ / 3.2 M NH ₄ OAc	<ol style="list-style-type: none"> 1. Add 6 mL of 0.02 M HNO₃. 2. Add 10 mL of 30% H₂O₂ adjusted to pH = 2 with HNO₃. 3. Hand shake for 1 minute. 4. Place into oven at 85 ± 2 °C for 2 hours. 5. Hand shake for 1 minute after 1 hour and 2 hours. 6. Add 6 mL H₂O₂ (pH = 2 with HNO₃) and hand shake for 1 minute. 7. Heat to 85 ± 2 °C for 3 hours. Shake for 1 minute each hour. 8. Allow sample to cool to room temperature. 9. Add 10 mL of 3.2 M NH₄OAc in 20% (v/v) HNO₃. 10. Add 8 mL deionized H₂O. 11. Shake for 30 minutes. 12. Repeat steps 3 through 8 in Extraction Step II.
VI	Residual	HF/HNO ₃	<ol style="list-style-type: none"> 1. Digest final residue using EPA Method 3052. 2. Analyze digest for U, V, Se, Mo, Ca, Mg, Na, Al, Fe, Mn, Si.

Notes:

Protocol from Tessier et al. 1979.

% - percent

µm - micrometer

°C - degrees Celsius

g - times gravity force

M - molar

mL - milliliter

v/v - by volume

Table 5
Sample Designation System
2019 Background Investigation
Grants Reclamation Project

First Field	Second Field	Third Field
Soil Samples		
Example: <i>BK1-C-1-2-012319</i> is a sample collected at borehole GF1-CS, from 1-2 feet below ground surface on January 23, 2019.		
Location	Depth	Date
Location ID as defined in Table 2	Sample depth range in feet below ground surface (e.g., minimum depth - maximum depth)	6-digit date code: mmddyy
Groundwater Samples		
Example: <i>BK1-C-012319</i> is a sample collected at monitoring well GF1-CS on January 23, 2019.		
Location	Date	--
Location ID as defined in Table 2	6-digit date code: mmddyy	--
Field Quality Control Samples		
Examples: <i>DUP-01</i> is the first duplicate sample to be collected during a sampling event; parent sample shall be recorded on field sampling forms and/or in the field notebook.		
Location ID	Duplicate number	--
For duplicates, "DUP" in place of boring ID	A number 01 through 100, not to be repeated in the same sampling event for the same sample type	--
For equipment blank, "EB" in place of boring ID	A number 01 through 100, not to be repeated in the same sampling event for the same sample type	--
For field blank, "FB" in place of boring ID	A number 01 through 100, not to be repeated in the same sampling event for the same sample type	--

Notes:

Matrix spike/matrix spike duplicate (MS/MSD) samples do not require a separate sample ID; samples intended for MS/MSD analysis should be indicated in the comment section of the chain-of-custody form.

-- = not applicable

DUP = duplicate

EB = equipment blank

FB = field blank

ID = identification

Table 6
Field Quality Control Samples and Frequencies
2019 Background Investigation
Grants Reclamation Project

Field Quality Control Sample Type	Description/Collection	Collection Frequency	Sample Analysis
Field Duplicate	Duplicate samples will be collected by filling two laboratory-supplied bottle sets at the same sampling location at the same time.	1 per 20 primary samples	Duplicate samples will be analyzed for each constituent analyzed for in the parent sample via select methods. ^a
MS/MSD	Double volume samples (two bottle sets) will be collected and submitted to the laboratory for MS/MSD.	1 per 20 primary samples	MS/MSD will be analyzed for each constituent analyzed for in the parent sample via select methods. ^a

Notes:

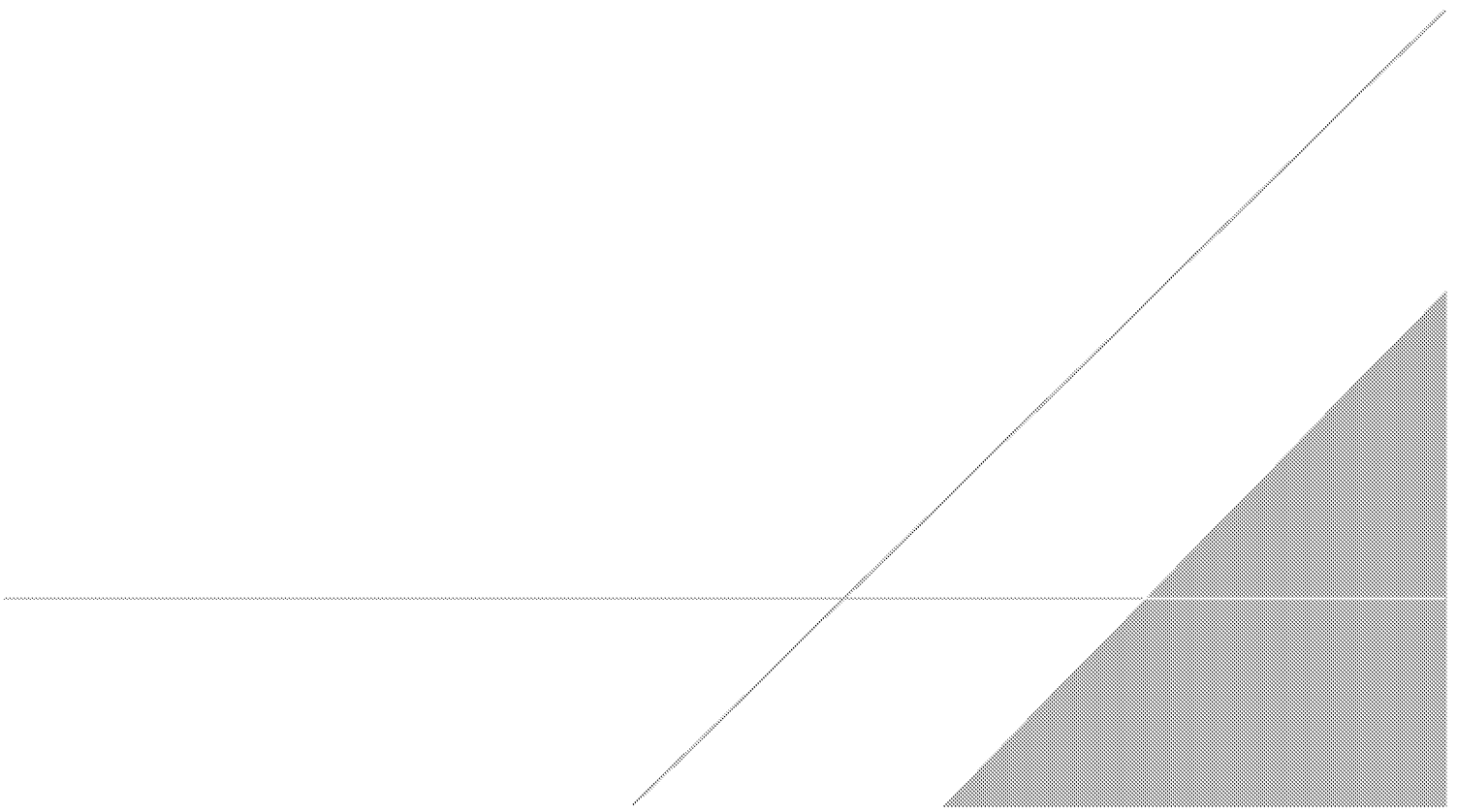
Field and/or equipment blanks may be collected according to Homestake Mining Company's groundwater sampling protocols.

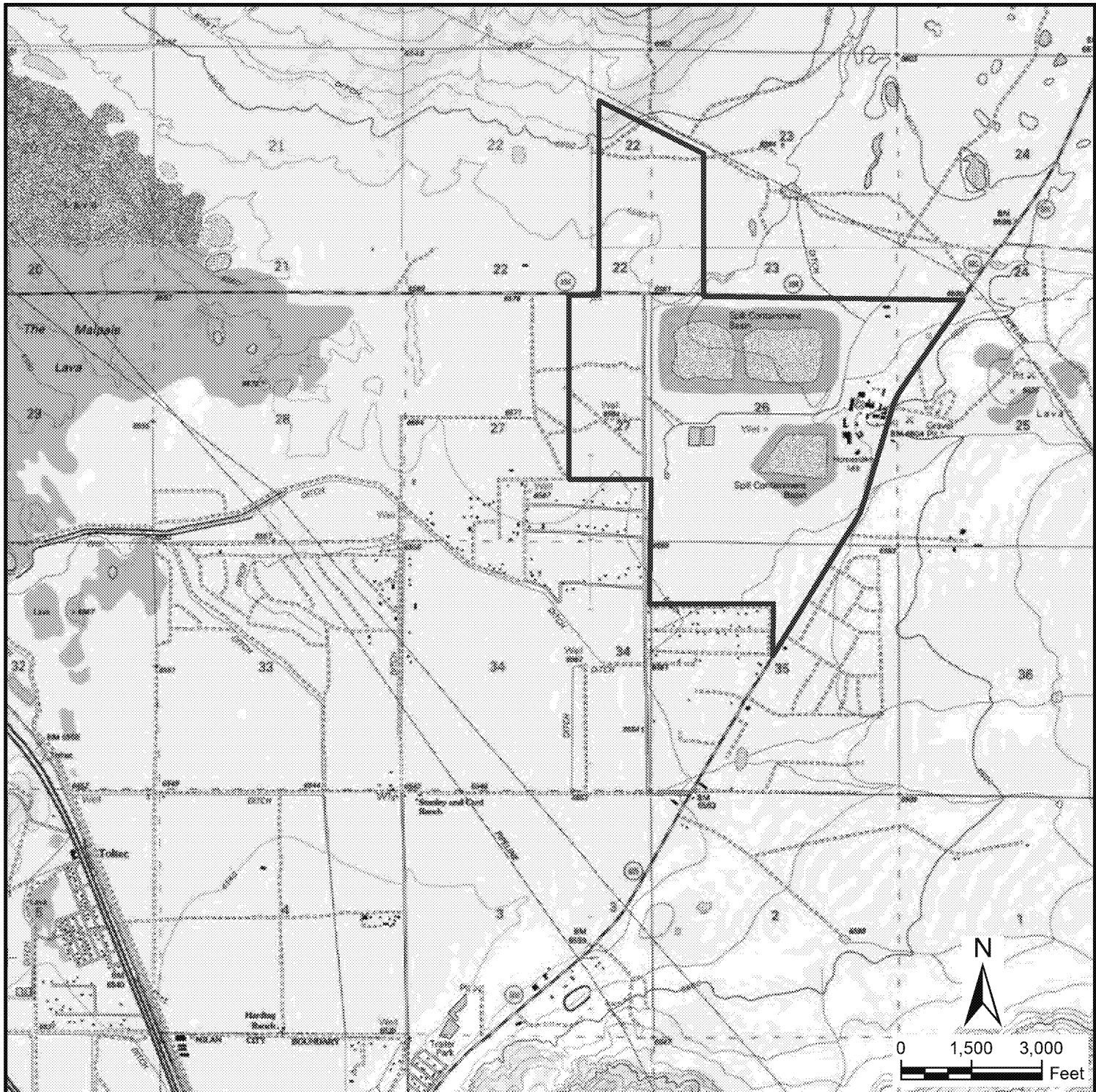
^a Duplicates and MS/MSDs will be analyzed/conducted for Total metals via USEPA Methods 3050B/6020B and total organic carbon and total sulfur via the LECO Induction Furnace method

USEPA = United States Environmental Protection Agency

MS/MSD = matrix spike/matrix spike duplicate

SAP
FIGURES

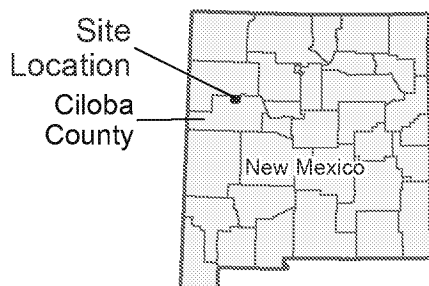




Source: USA Topo Maps, serviced by ESRI ArcGIS Online

LEGEND:

 Nuclear Regulatory Commission License Boundary



SAMPLING AND ANALYSIS PLAN
2019 BACKGROUND INVESTIGATION
GRANTS RECLAMATION PROJECT

SITE LOCATION MAP



FIGURE
1



LEGEND

- Existing alluvial aquifer wells planned for downhole geophysical logging including natural gamma, spectral gamma, and induction conductivity (see Note 1)
- New Borehole Locations
- Alluvial Borehole
- Fault
- Proposed Electrical Resistivity Line
- DD-BK** 2018 Borehole Location

Subcrop* of Upper Chinle Alluvium Overlies Sandstone

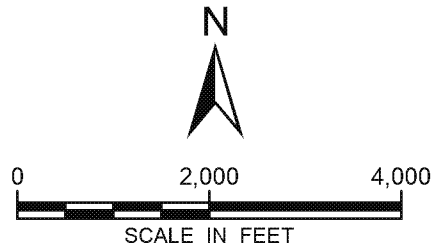
- Saturated Alluvium

Subcrop* of Middle Chinle Alluvium Overlies Sandstone

- Saturated Alluvium
- Unsaturated Alluvium

* Subcrop boundary dashed where inferred.

- Notes:
- 1) Only spectral gamma data will be collected for wells DD, DD2, MV, ND, and Q.
 - 2) Four new borehole locations will be advanced along the resistivity lines; the locations shown on this map are based upon completion of the ERT survey.
 - 3) Four new wells (at locations BK1 and BK2) will undergo downhole geophysical assessment via natural gamma, spectral gamma, and induction conductivity, boreholes BK3 and BK4 will also undergo geophysical assessment.



Basemap features from:
Hydro-Engineering, LLC, 2011

SAMPLING AND ANALYSIS PLAN
2019 BACKGROUND INVESTIGATION
GRANTS RECLAMATION PROJECT

APPROXIMATE LOCATIONS OF
PLANNED ACTIVITIES

ARCADIS

FIGURE
2

SAP

APPENDIX A

Quality Assurance Project Plan





Homestake Mining Company of California

QUALITY ASSURANCE PROJECT PLAN: 2019 BACKGROUND INVESTIGATION

Grants Reclamation Project
Grants, New Mexico

May 2019, Revision: 1



Jennifer Singer
Quality Assurance Manager



Shannon Ulrich
Technical Lead

QUALITY ASSURANCE PROJECT PLAN: 2019 BACKGROUND INVESTIGATION

Grants Reclamation Project
Grants, New Mexico

Prepared for:
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CO000120.1901

Date:
May 2019

Revision: 1

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QUALITY ASSURANCE PROJECT PLAN: 2019 BACKGROUND INVESTIGATION

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EXHIBIT

Exhibit 1 Project Team Organization Chart

ACRONYMS AND ABBREVIATIONS

ACZ	ACZ Laboratories, Inc.
Arcadis	Arcadis U.S., Inc.
CDPHE	Colorado Department of Public Health and Environment
CLP	Contract Laboratory Program
COC	chain-of-custody
CSM	conceptual site model
DCM	DCM Science Laboratory
DQO	data quality objective
EDD	electronic data deliverable
ELI	Energy Laboratories, Inc.
EQulS	Environmental Quality Information System
ERT	electrical resistivity tomography
GRP	Grants Reclamation Project
GWPS	Groundwater Protection Standard
Hazen	Huffman Hazen Laboratories
HMC	Homestake Mining Company of California
ID	identification
IT ²	Isotope Tracer Technologies, Inc.
LCS	laboratory control sample
LTP	large tailing pile
MDL	method detection limit
MS	matrix spike
MSD	matrix spike duplicate
NIST	National Institute of Standards and Technology
NMED	New Mexico Environmental Department
NRC	Nuclear Regulatory Commission
QA	quality assurance
QAM	Quality Assurance Manager
QAPP	Quality Assurance Project Plan

QUALITY ASSURANCE PROJECT PLAN: 2019 BACKGROUND INVESTIGATION

QC	quality control
RL	reporting limit
RPD	relative percent difference
SAP	Sampling and Analysis Plan: 2019 Background Investigation
SDG	sample delivery group
Site	Grants Reclamation Project located in Grants, New Mexico
SOP	Standard Operating Procedure
USGS	U.S. Geological Survey
USEPA	United States Environmental Protection Agency

1 INTRODUCTION

This Quality Assurance Project Plan (QAPP) provides quality assurance/quality control (QA/QC) procedures associated with the 2019 Background Investigation as described in the associated Sampling and Analysis Plan (SAP) prepared for the Homestake Mining Company of California (HMC) Grants Reclamation Project (GRP) located in Grants, New Mexico (Site). Arcadis U.S., Inc. (Arcadis) prepared this QAPP on behalf of HMC. This QAPP describes the policies and procedures for ensuring that work processes and products satisfy stated expectations or specifications.

The field activities covered in the SAP include an electrical resistivity tomography (ERT) assessment, downhole geophysical characterization in several existing monitoring wells, installation of two boreholes to conduct lithologic logging, soil sampling and correlated geophysical characterization of lithologies within the borings, and analysis of results from groundwater sampling performed by HMC.

This QAPP is intended to guide field sampling and field and laboratory measurement activities conducted as part of the work performed by Arcadis in accordance with the SAP. To the extent that other work plans are written and approved relevant to this QAPP, those work plans will build on and refer to the information provided in this QAPP to document a complete QA program.

1.1 Objectives

The objective of this QAPP is to document the data quality specifications and methods that will be used to establish technical accuracy and precision, statistical validity, and documentary evidence of environmental data generated during field activities conducted at the Site.

1.2 Distribution and Revision

This QAPP is a controlled document. Controlled distribution will be implemented to ensure that only the most current approved version is used. A sequential revision numbering system will be in place to identify changes in the controlled versions of this QAPP. Versions will be provided to managers, QA coordinators, field personnel, and subcontractor representatives, if applicable.

Addenda, updates, or revisions to this QAPP may be prepared if guidelines, procedures, regulatory documents are revised, or if project objectives, scope, or site activities change.

2 PROJECT MANAGEMENT

The activities to be completed under the SAP will require integration of personnel from the following organizations, identified in the project team organization chart presented below in Exhibit 1, collectively referred to as the “project team”:

- Regulatory Agencies
 - Nuclear Regulatory Commission (NRC)
 - United States Environmental Protection Agency (USEPA)
 - New Mexico Environmental Department (NMED)
- HMC
- Arcadis
- Laboratories
 - Energy Laboratories, Inc. in Casper, Wyoming (ELI)
 - DCM Science Laboratory in Wheat Ridge, Colorado (DCM), subcontracted through ELI
 - ACZ Laboratories, Inc. in Steamboat Springs, Colorado (ACZ)
 - Huffman Hazen Laboratories in Golden, Colorado (Hazen)
 - Isotope Tracer Technologies, Inc. in Waterloo, Ontario (IT2)

The primary end data users for the project who will be provided copies of this QAPP, as indicated in the organization chart, include HMC and its consultants, contractors and subcontractors, and the analytical laboratories, as well as the appropriate regulatory agencies as determined by the HMC Project Manager (PM).

QUALITY ASSURANCE PROJECT PLAN: 2019 BACKGROUND INVESTIGATION

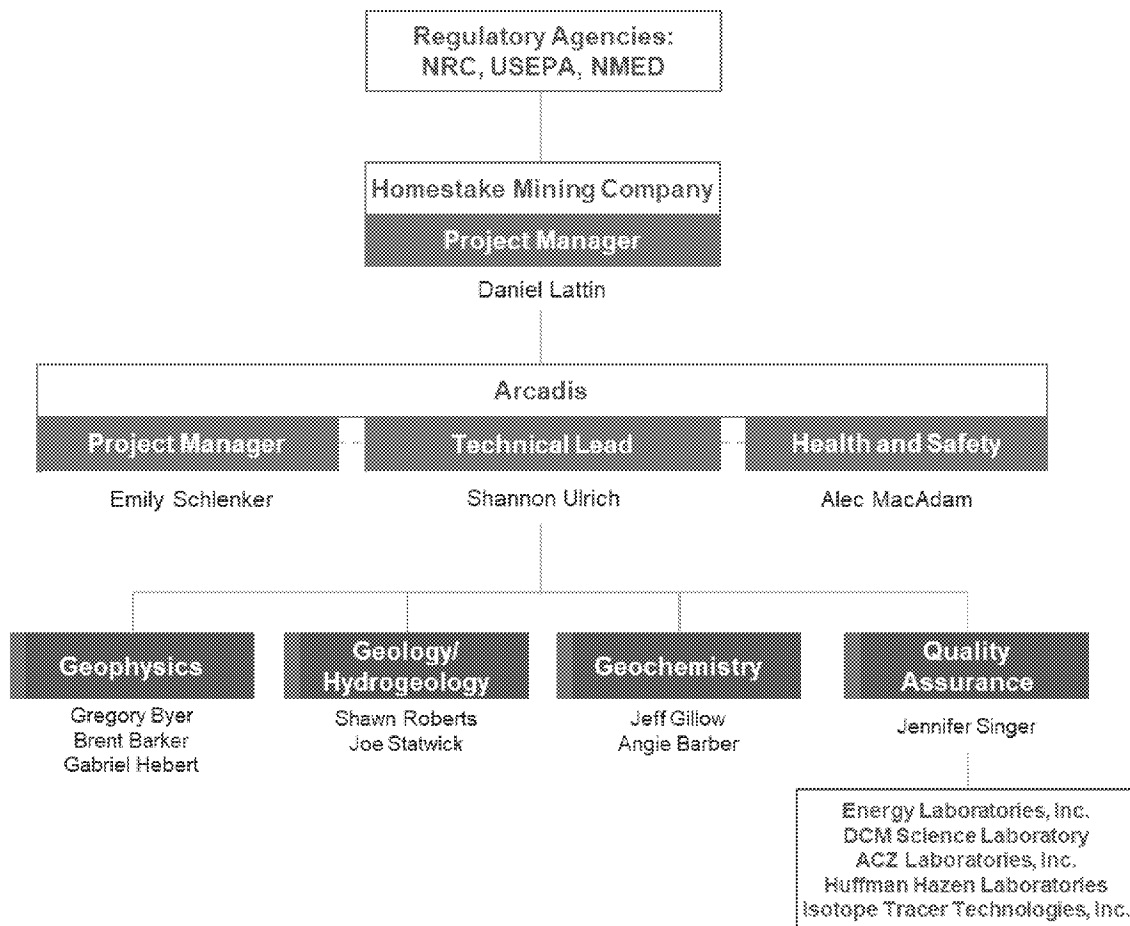


Exhibit 1. Project team organization chart.

3 PROJECT DATA QUALITY OBJECTIVES

Data Quality Objectives (DQOs) were developed in accordance with the USEPA's 7-step DQO Process presented in Guidance on Systematic Planning Using the Data Quality Objectives Process, USEPA QA/G-4, EPA/240/B-06/001, February 2006 (USEPA 2006). As described in this guidance, the DQO process is used to develop performance and acceptance criteria (or DQOs) that clarify study objectives, define the appropriate type of data, and specify tolerable levels of potential decision errors that will be used as the basis for establishing the quality and quantity of data needed to support decisions. The DQO process identifies the problem, the goal of the study, the information inputs, the boundaries of the study, the analytical approach, performance and acceptance criteria, and the plan for obtaining data, as follows:

Step 1: State the Problem
<p>Stakeholder groups have requested a better understanding of site-specific background water quality standards and the occurrence of uranium in the alluvial system at the GRP. In 2016, the USEPA, with the assistance of the United States Geological Service (USGS), initiated a reassessment of site background water quality standards and included well reconnaissance, geophysics, and sampling of groundwater via micropurge, volume purge, and passive sampling techniques. Arcadis was engaged by HMC to collect split samples with the USGS during the 2016 sampling events.</p> <p>Arcadis' interpretation of data collected during split sampling and a subsequent soil investigation is that groundwater uranium concentrations in near-upgradient alluvial wells are attributed to locally naturally-occurring uranium in soils. Arcadis prepared a detailed report (Arcadis 2018a) that is included as an appendix in a white paper (Arcadis 2018b) documenting this conceptual site model (CSM). The white paper was provided to USEPA and NMED and the findings were discussed in subsequent meetings between the USEPA, NMED, HMC, NRC, and Arcadis. In order to address technical inquiries from the USEPA and NMED relating to the CSM, a supplemental background investigation is necessary.</p>
Step 2: Identify the Goal of the Study
<p>The primary goal of the supplemental background investigation at the GRP is to refine the CSM for natural uranium distribution and transport by identifying the lithological and hydraulic conductivity heterogeneity as well as the local variation in uranium concentrations across the alluvial channel upgradient (north) of the large tailing pile (LTP).</p>
Step 3: Identify Information Inputs
<p>The data needed to accomplish the goals of the supplemental background investigation are as follows:</p> <ul style="list-style-type: none"> • Lithology and stratigraphy of the alluvial channel north of the LTP, including visualization of channel geometry and high-permeability zones containing coarse-grained materials; • In-situ alluvium concentrations of uranium, thorium, and potassium to 1) identify relationships between naturally occurring uranium and litho-stratigraphic conditions, mineralogies, and geochemical parameters and 2) interpretation of the provenance of the alluvial sediments using the thorium-potassium ratios;

<ul style="list-style-type: none"> Mineralogical and geochemical data as well as uranium and other element concentrations from both fine-grained and coarse-grained sediments; and Temporal trends in geochemical data and uranium concentrations in groundwater associated with (i.e., separately screened across) fine-grained and coarse-grained sediments.
Step 4: Define the Boundaries of the Study
<p>Geophysical, lithological, and sampling activities to obtain the data needed to support the goals of the supplemental background investigation will include new boreholes and wells located along a cross-section across the alluvial channel as well as existing alluvial aquifer wells north of the LTP at the GRP.</p>
Step 5: Develop the Analytical Approach
<p>Geophysical assessments include an ERT assessment and downhole geophysical logging.</p> <ul style="list-style-type: none"> ERT assessment data will be used to inform the drilling phase of the program as well as to map the alluvial channel geometry and high-permeability zones. Downhole geophysical logging of existing and new boreholes/wells will provide a common set of detailed, quantitative, in-situ measurements to link interpretations between visual geologic descriptions, lithology of alluvial material surrounding existing monitoring wells where visual descriptions may be unavailable or of low detail, and the large-scale ERT cross-sections. <p>Lithological assessment and installation of two groundwater wells will be conducted at two different locations along the ERT transects.</p> <ul style="list-style-type: none"> Soil sampling during advancement of the boreholes will provide geochemical data from both fine-grained and coarse-grained sediments. The groundwater monitoring wells will be installed with short screen intervals separately screened across the fine-grained and coarse-grained sediments to assess the associated geochemical trends in groundwater. <p>The results will be used to refine the CSM.</p> <ul style="list-style-type: none"> Groundwater data reflecting that higher uranium concentrations are associated with the finer-grained sediments would indicate that uranium was naturally emplaced during fluvial deposition and is being released into groundwater locally by natural processes. Conversely groundwater data reflecting that higher uranium concentrations are associated with the coarser-grained, high hydraulic conductivity sediments could suggest that uranium in groundwater may be present because of regional groundwater sources.
Step 6: Specify Performance or Acceptance Criteria
<p>Measurement performance criteria are specified in Section 10.3 of this QAPP. Groundwater data will be compared to the Site Groundwater Protection Standards (GWPSs).</p>
Step 7: Develop the Plan for Obtaining Data
<p>This SAP presents the rationale and plan, including field and analytical methods, for obtaining geophysical, lithological, and soil and groundwater sampling data.</p>

4 LEVELS OF DATA REPORTING

For the purposes of the assessment, three levels of data reporting are defined here. The appropriate data reporting level will be specified with each analytical laboratory request; Level 1 and Level 2 reporting will be the most common reporting type used on this project.

Level 1 – Minimal Reporting. Minimal or “results only” reporting is used for analyses that, due either to their nature (i.e., field monitoring or specialty analyses that do not follow USEPA reporting protocols such as X-ray Diffraction or stable isotope analyses) or the intended data use (i.e., preliminary screening), do not generate or require extensive supporting documentation.

Level 2 – Modified Reporting. Modified reporting is used for analyses that are performed following standard USEPA-approved methods and QA/QC protocols. Based on the intended data use, modified reporting may require some supporting documentation, but not full Contract Laboratory Program (CLP)-type reporting. Level 2 laboratory data report-required elements are method-specific and may include, but are not limited to, the following:

- COC
- Case narrative
- Final parameter concentration for all samples
- Preparation or extraction and analysis dates/times
- Method blanks
- Matrix spike (MS) and matrix spike duplicate (MSD) recoveries and relative percent difference (RPD)
- Laboratory duplicate RPD
- Laboratory control sample (LCS) recoveries
- Counting uncertainty and confidence intervals (if applicable)

Level 4 – Full Reporting: Full “CLP-type” reporting is used for those analyses that, based on the intended data use, require full documentation. Level 4 laboratory data report-required elements are method-specific. They may include some or all of the elements for Level 2 listed above and may also include, but are not limited to, the following:

- Calibrations (initial and continuing)
- Instrument blanks
- Internal standard areas
- Serial dilution %D
- Raw data output for project samples and associated QA/QC samples

5 SPECIAL TRAINING REQUIREMENTS/CERTIFICATION

Copies of training certificates and records for Arcadis personnel working onsite will be kept with Arcadis' Training Department. Arcadis employees are provided training, as necessary, for the completion of projects, as determined by Arcadis' corporate Health and Safety Officer and Education and Training Department.

6 DOCUMENTATION AND RECORDS

Documents and records are retained in the Arcadis offices, as well as at offsite storage facilities. Records accessed less frequently than once per month may be sent to storage and retrieved, as needed. Electronic documents, data, databases, and electronic communication will be stored within files and folders located on computerized hard disk servers.

7 FIELD PROCEDURES

This section details general QA/QC requirements for the field activities described in the SAP.

7.1 Field Equipment

Instruments and equipment used by Arcadis to gather, generate, or measure environmental data will be calibrated and maintained according to manufacturer specifications, and in such a manner that accuracy and reproducibility of results are consistent with the manufacturer's specifications.

7.1.1 Maintenance and Inspection

Each piece of field equipment used by Arcadis in support of the field sampling activities that directly affect the quality of the analytical data will be subject to preventative maintenance measures that minimize equipment downtime. Equipment will be examined to ensure that it is in operating condition. When available, field notes from previous sampling events will be reviewed to ensure that any prior equipment problems are not overlooked, and that any necessary repairs to equipment have been carried out.

Prior to field sampling activities, each piece of field equipment will be inspected to ensure that it is operational. If the equipment is not operational, it will be taken out of use until it can be serviced. Meters that require charging or batteries will be fully charged, and fresh batteries will be kept on hand. If instrument servicing is required, it is the responsibility of the field personnel to follow the maintenance schedule and arrange for timely service.

7.1.2 Calibration

Field monitoring and detection equipment will be routinely calibrated according to manufacturer specifications. To demonstrate that established calibration procedures have been followed, calibration records will be prepared and maintained on the appropriate logs.

If a calibrated instrument fails to meet calibration verification, it will be removed from use until it can be serviced. Equipment found to be out of tolerance during the period of use will be removed from use, and measuring and testing activities performed using the equipment will be noted as such on the field logs.

7.2 Field Data Documentation

Field personnel will provide comprehensive documentation covering each aspect of field sampling, field analysis, and sample COC as specified in the SAP and herein. This documentation provides records of activities and allows for reconstruction of all field events to aid in the data review and interpretation process. Documents, records, and information relating to the performance of the field work will be retained in the project file.

Each page or entry of field notes will be dated and initialed by the field personnel at the time of entry. Errors in entry will be crossed out in indelible ink with a single stroke, corrected without the use of white-out or by obliterating or writing directly over the erroneous entry, and initialed and dated by the individual

making the correction. Pages that are not used will be completed by lining out unused portions. To ensure at any future date that pages are not missing, each page will be sequentially numbered.

7.2.1 Field Logs

Field logs will provide the means of recording the data collection activities that are performed. As such, entries will be described in as much detail as possible so that persons going to the Site could reconstruct a particular situation without reliance on memory. Information collected in the field through visual observation, manual measurement, and/or field instrumentation will be recorded on the field logs. The specific field logs to be used are described in the SAP.

7.2.2 Field Chain-of-Custody Forms

Chain-of-custody (COC) forms are used as a means of documenting and tracking sample possession from time of collection to the time of disposal. Every field sample collected will be documented on an appropriate COC form. Field personnel will be briefed on the proper use of the COC procedure.

Completed COC forms will be required for the samples to be analyzed. COC forms will be initiated by the sampling crew in the field. The COC forms will contain the unique sample identification (ID), sample date and time, sample description, sample type, preservation (if any), and analyses required. The original COC form will accompany the samples to the laboratory. Copies of the COC form will be made prior to shipment (or multiple copy forms will be used) for field documentation. The COC forms will remain with the samples at all times. The samples and signed COC forms will remain in the possession of the sampling crew until the samples are delivered to the express carrier (e.g., FedEx), hand delivered to a permanent laboratory, or placed in secure storage.

7.3 Sample Collection Procedures

Arcadis will collect soil and/or groundwater samples as described in the SAP.

7.3.1 Sample Containers and Preservatives

The analytical laboratory will supply appropriate sample containers and preservatives, as necessary. Field personnel will be responsible for properly labeling containers and preserving samples (as appropriate). Sample labeling procedures are discussed in Section 7.3.3. Samples containers, preservation requirements, and holding times for each method are provided in Table 3 of the SAP.

7.3.2 Sample Collection Methods

Sample collection methods are described in the SAP.

7.3.3 Sample Labeling

Sample labels will be completed for each sample using waterproof ink. Completed sample labels will be affixed to each sample bottle.

The following information is required on each sample label:

- Project name
- Sample ID
- Date collected
- Time collected
- Location
- Sampler
- Analysis to be performed
- Preservative, if any

7.3.4 Sample Identification Numbers

Samples will be identified with a unique sample ID that will facilitate sample tracking. Sample IDs for primary samples and QA/QC samples are provided in Table 5 of the SAP.

Primary samples selected for MS/MSD analysis will be clearly identified on the COC notes section as MS/MSD samples and not unique samples. Double volume samples (i.e., two bottle sets) will be submitted for MS/MSD analysis.

7.3.5 Field Custody Procedures

The objective of field sample custody is to ensure that samples are not tampered or modified from the time of collection through transport and transfer to the analytical laboratory. Persons will have “custody of samples” when the samples are in their physical possession, in their view after being in their possession, or in their physical possession and secured so they cannot be tampered with. In addition, when samples are secured in a restricted area accessible only to authorized personnel, they will be deemed in the custody of such authorized personnel. Field custody documentation consists of both field logs and field COC forms.

Measures will be taken during the field investigation to prevent samples and records from being lost, damaged, or altered. When not in use, all field logs will be stored in a secure location. An electronic copy (e.g., scan to pdf) of all final field data and laboratory data will be kept in the project file.

7.3.6 Sample Handling, Packing, and Shipping Requirements

Sample packaging and shipment procedures are designed so that the samples will arrive at the laboratory, with the COC, intact.

Samples will be packaged for shipment as outlined below:

- Securely affix the sample label to the container with clear packing tape; or alternatively, clearly write the sample label information directly on the sampling container using a permanent marker.
- Check the cap on the sample container to confirm that it is properly sealed.

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- Complete the COC form with the required sampling information and confirm that the recorded information matches the sample labels. NOTE: If the designated sampler relinquishes the samples to other sampling or field personnel for packing or other purposes, the sampler will complete the COC prior to this transfer. The appropriate personnel will sign and date the COC form to document the sample custody transfer.
- Wrap glass sample containers in bubble wrap or other cushioning material.
- Place 1 to 2 inches of cushioning material at the bottom of the cooler or shipping container.
- Place the sealed sample containers into the cooler or shipping container.
- If required, place ice in plastic bags, seal the bags, and place the bags loosely in the cooler.
- Fill the remaining space in the cooler with cushioning material. Samples not requiring cold shipment will be packed with sufficient material to avoid shifting and deformation during shipment.
- Place COC forms in a plastic bag and seal. Tape the forms to the inside of the cooler lid.
- Wrap strapping tape (or equivalent) around both ends of the cooler at least twice.
- Mark the cooler on the outside with the shipping address and return address, affix "Fragile" labels, and draw (or affix) arrows indicating "this side up." Cover the labels with clear plastic tape. If the samples are being delivered directly to the laboratory or will be picked up by the laboratory's courier service, this step is eliminated.
- Place a signed custody seal over the sample cooler lid.

Samples will be packaged by field personnel and transported as low-concentration environmental samples. The samples will be hand delivered or delivered by a commercial carrier. In some cases, the analytical method may require analysis within a shorter holding time, and arrangements will need to be made to accommodate laboratory requirements. Shipments will be accompanied by the COC form identifying the contents. The original form will accompany the shipment; copies will be retained by the sampler for the sampling office records. If the samples are sent by common carrier, either a pre-printed shipping label generated by the laboratory or a bill of lading will be used. Receipts or bills of lading will be retained as part of the permanent project documentation. Commercial carriers are not required to sign off on the COC form as long as the forms are sealed inside the sample cooler or shipping container, and the custody seals remain intact.

8 LABORATORY PROCEDURES

The following laboratories will perform the laboratory analyses. The SAP specifies which analyses will be performed by each laboratory.

Laboratory	Relevant Accreditations/Certifications
Energy Laboratories, Inc.	NMED Drinking Water, Laboratory #WY00002, effective through June 30, 2019 National Environmental Laboratory Accreditation Conference NRC Materials License 49-26846-01, effective through September 30, 2023
DCM Science Laboratory, Inc. (subcontracted by ELI)	AIHA LAP, LLC accreditation since 1986 NVLAP accreditation since 1989
ACZ Laboratories, Inc.	NMED Drinking Water Laboratory Certification Program, effective through July 31, 2019
Huffman Hazen Laboratories	USGS certified for low-levels of metals in natural waters Colorado Department of Public Health and Environment (CDPHE) certified for analytes in drinking water Certifies select Standard Reference Materials for the National Institute of Standards and Technology (NIST)
Isotope Tracer Technologies, Inc.	Not applicable

8.1 Laboratory Parameters and Methods

Samples collected by Arcadis during the 2019 field activities will be soil samples. Groundwater samples will be collected by HMC. Analytical parameters and methods, preservation requirements, and holding times are included in the SAP.

Laboratory analytical requirements presented in the subsections below include a general summary of requirements. When available, current approved USEPA methods will be used for the parameters of interest. Specialty methods will be used for non-routine analyses for which USEPA methods are not available, and these will be documented.

The primary sources for methods used in this sampling program are provided in the following documents:

- Test Methods for Evaluating Solid Waste, SW-846 Third Edition, Update 4, USEPA, December 1996.
- Methods for Chemical Analysis of Water and Wastes, EPA-600/4-79-020, USEPA, 1983.
- Standard Methods for the Examination of Water and Wastewater, 23rd Edition, American Water Works Association, 2017.

Additional sampling and method references provided will be documented in the project file and reported as references in data reports.

8.2 Laboratory Instruments and Equipment

Instrument calibration will follow the specifications provided by the instrument manufacturer or specific analytical method used. Records of calibrations will be filed and maintained by the laboratory.

All standards used to calibrate laboratory equipment are traceable, directly or indirectly, to the NIST; any deviation will be documented and described and approved by the laboratory QA Manager (QAM).

8.3 Laboratory Custody Procedures

8.3.1 General

Upon sample receipt, laboratory personnel will be responsible for sample custody. The original field COC form will accompany all samples requiring laboratory analysis. Samples will be kept secured in the laboratory until all stages of analysis are complete. All laboratory personnel having samples in their custody will be responsible for documenting and maintaining sample integrity.

8.3.2 Sample Receipt and Storage

Immediately upon sample receipt, the laboratory sample custodian will verify the integrity of the cooler or shipping container, integrity of the seal, open the cooler/shipping container, and compare the contents against the field COC. If a sample container is missing, a sample container is received broken, the sample is in an inappropriate container, or the sample has not been preserved by appropriate means, the Arcadis QAM will be notified. The laboratory sample custodian will be responsible for logging the samples in, assigning a unique laboratory identification number to each sample, labeling the sample bottle with the laboratory identification number, and moving the sample to an appropriate storage location to await analysis. The project name, field sample code, date sampled, date received, analysis required, storage location and date, and action for final disposition will be recorded in the laboratory tracking system. Relevant custody documentation will be placed in the project file.

8.3.3 Sample Analysis

Analysis of an acceptable sample will be initiated by a worksheet that will contain pertinent information for analysis. The routing sheet will be forwarded to the analyst, and the sample will be moved into an appropriate storage location to await analysis. The document control officer will file COC forms in the project file.

Samples will be organized into sample delivery groups (SDGs) by the laboratory (as applicable for specialty analyses). An SDG may contain up to 20 field samples (field duplicates, trip blanks, equipment blanks, and rinse blanks are considered field samples for the purposes of SDG assignment). All field samples assigned to a single SDG will be received by the laboratory on the same day and must be processed through the laboratory (preparation, analysis, and reporting) as a group. If re-analysis of a sample is required, it may be rerun separately from the original SDG; however, the resulting data will be reported with the original SDG.

Information regarding the sample, analytical procedures performed, and the results of the testing will be recorded in a laboratory notebook by the analyst. These notes will be dated and identify the analyst, instrument used, and instrument conditions.

8.3.4 Sample Storage Following Analysis

Samples will be maintained by the laboratory for at least 1 month (or as prescribed in the laboratory Standard Operating Procedure [SOP] or as requested by Arcadis for specific samples) after the final report is delivered. The laboratory will be responsible for the eventual and appropriate disposal of the samples. The analytical laboratory will inform the environmental consultant before any samples are disposed. Unused portions of the samples, sample extracts, and associated wastes will be disposed by the laboratory in accordance with applicable rules and regulations.

8.4 Laboratory Data Documentation

8.4.1 Laboratory Project Files

The laboratory will establish a file for pertinent data. The file will include correspondence, faxed information, phone logs, and COC forms. The laboratory will retain project files and data packages for a period not less than 5 years.

8.4.2 Laboratory Logbooks

Workbooks, bench sheets, instrument logbooks, and instrument printouts will be used to trace the history of samples through the analytical process and to document important aspects of the work, including the associated QC checks. As such, logbooks, bench sheets, instrument logs, and instrument printouts will be maintained by the laboratory.

Each page or entry will be dated and initialed by the analyst at the time of entry. Errors in entry will be crossed out in indelible ink with a single stroke, corrected without the use of white-out or by obliterating or writing directly over the erroneous entry, and initialed and dated by the individual making the correction. Pages of logbooks that are not used will be completed by lining out unused portions.

Information regarding the sample, analytical procedures performed, and the results of the testing will be recorded on laboratory forms or personal notebook pages by the analyst. These notes will be dated and will also identify the analyst, the instrument used, and the instrument conditions.

8.4.3 Computer and Hard Copy Storage

All electronic files and deliverables will be retained by the laboratory for not less than 5 years; hard copy data packages (or electronic copies) will also be retained for not less than 5 years.

9 DATA MANAGEMENT

The purpose of data management is to provide for the accuracy and ready accessibility of all necessary data to meet the analytical and reporting objectives of the project.

The data management program established for the project includes field documentation and sample QA/QC procedures, methods for tracking and managing the data, and a system for filing all site-related information. More specifically, data management procedures will be employed to efficiently process the information collected such that the data are readily accessible and accurate. These procedures are described in detail in the following section.

The data management plan has four elements: 1) sample designation system, 2) data collection activities, 3) sample tracking and management, and 4) data management system.

9.1 Sample Designation System

A concise and easily understandable sample designation system is an important part of project sampling activities. It provides a unique sample number that will facilitate both sample tracking and easy resampling of select locations to evaluate data gaps, if necessary. The sample designation system to be employed during the sampling activities will be consistent, yet flexible enough to accommodate unforeseen sampling events or conditions. A combination of letters and numbers will be used to yield a unique sample ID for each field sampled collected. The sample designation system is provided in Table 5 of the SAP.

9.2 Sample Tracking and Management

A record of all field documentation will be maintained to provide verification of the validity of data used in the site analysis. To effectively execute such documentation, specific sample tracking and data management procedures will be used throughout the sampling program.

Sample tracking will begin with the completion of COC forms. The completed COC forms associated with samples collected will be faxed and/or scanned and emailed to the Arcadis QAM or designee. The Arcadis QAM or designee will compare the COC forms against the sampling plan to ensure that all samples were collected and all analyses were requested. Copies of all completed COC forms will be maintained in the Arcadis office and will be provided to HMC upon request. The Arcadis QAM or designee will verify the delivery of samples using express carrier tracking numbers. The laboratory will verify receipt of the samples electronically (via email) as soon as practicable.

When analytical data are received from the laboratory, the Arcadis QAM or designee will review the incoming analytical data packages against the information on the COCs to confirm that the correct analyses were performed for each sample and that results for all samples submitted for analysis were received. Any discrepancies noted will be promptly followed up on with the laboratory by the Arcadis QAM.

9.3 Data Management System

In addition to the sample tracking system, a data management system will be implemented. The central focus of the data management system will be the development of a personal computer-based project database. The project database will combine pertinent geographical, field, and analytical data. Information that will be used to populate the database will be derived from two primary sources: field observations and analytical results. Each of these sources is discussed in the following sections.

9.3.1 Computer Hardware

The database will be constructed on personal computer work stations connected through a network server. The network will provide access to various hardware peripherals, such as laser printers, backup storage devices, image scanners, and modems. Computer hardware will be upgraded to industrial and corporate standards, as necessary, in the future.

9.3.2 Computer Software

The data will be warehoused in Environmental Quality Information System (EQulS) 6 Enterprise system that uses an SQL Server database. Geographic information system applications will be developed in ESRI ArcGIS, with additional customization performed with Visual Basic. Tables and other database reports will be generated through Microsoft Access in conjunction with Microsoft Excel and/or Microsoft Word. These software products will be upgraded to current industrial standards, as necessary.

9.3.3 Field Observations

An important part of the information that will ultimately reside in the data management system for use during the project will include the observations that are recorded in the field.

During each sampling event, appropriate field documentation will be prepared by the field personnel who performed the sampling activities. The purpose of the documentation is to create a summary and a record of the sampling event. Items to be included are discussed in the SAP.

Field observations recorded on field logs will be reviewed by the Arcadis QAM for adherence to the SAP and for consistency. Concerns identified as a result of this review will be discussed with the field personnel, corrected if possible, and (as necessary) incorporated into the data evaluation process.

If applicable, field data forms and calculations will be processed and included in appendices to the appropriate reports (when generated). The original field logs, documents, and data reductions will be kept in the project file.

9.3.4 Analytical Results

Where the laboratories have the capability, analytical results will be reported in the electronic data deliverable (EDD) or other approved electronic table-based format. Laboratory reports (results sheets) in a pdf or electronic spreadsheet format will be received from all laboratories, within the timeframe specified in the contract agreement.

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Where the laboratories have the capability, the laboratory is responsible for preparing Level 2 (or similar) data packages (as defined previously) for all samples. In general, data reports for all parameters will include the following items:

- Narrative: Summary of activities that took place during the course of sample analysis, including the following information:
 - Laboratory name and address
 - Date of sample receipt
 - Cross-reference of laboratory identification number to sample ID
 - Analytical methods used
 - Deviations from specified protocol
 - Corrective actions taken

Included with the narrative will be any sample handling documents, including field and internal COC forms, air bills, and shipping tags.

- Analytical Results: These will be reported according to the method and analysis type and may include, but are not limited to, the following information, as applicable:
 - Sample ID
 - Laboratory ID
 - Date of collection
 - Date of receipt
 - Date of extraction
 - Date of analysis
 - Dilution factor
 - Detection limits
 - Counting uncertainty and confidence levels

Sample results on the report forms will be corrected for dilutions. Unless otherwise specified, results will be reported uncorrected for blank contamination.

Analytical results will be provided by the laboratory in digital format. The data packages will be examined to confirm that the correct analyses were performed for each sample submitted and that all analyses requested on the COC form were performed. If discrepancies are noted, the Arcadis QAM will be notified and will promptly follow up with the laboratory to resolve any issues.

The individual EDDs, supplied by the laboratory in EQUIS 6 file format or other approved table-based format, will be loaded into the appropriate database. Analytical data that cannot be provided by the laboratory in electronic format will be entered manually into a spreadsheet program to facilitate the entry and processing of the data to the database. After entry into the database, the EDD data will be compared

to the field information previously entered into the database to confirm that all requested analytical data have been received.

9.3.5 Data Analysis and Reporting

The database management system will have several functions to facilitate the review and analysis of the data. Routines have been developed to permit the user to scan analytical data from a given site for a given media. Several output functions are also available that can be modified, as necessary, for use in the data management system.

A valuable function of the data management system will be the generation of tables of analytical results from the project databases. The capability of the data management system to directly produce tables reduces the redundant manual entry of analytical results during report preparation and precludes transcription errors that may occur otherwise. This data management system function creates a digital file of analytical results and qualifiers for a given media. The file can then be processed into a table of rows and columns that can be transferred to a word processing software (e.g., Microsoft® Excel) for final formatting and addition of titles and notes. Tables of analytical data will be produced as part of data interpretation tasks and the reporting of data to the client. Analytical data may also be provided to the agencies, as determined by the HMC PM.

The data management system also has the capability of producing a digital file of select parameters that exists in one or more of the databases. This type of custom function is accomplished on an interactive basis and is best used for transferring select information into a number of analysis tools, such as statistical or graphing programs.

10 QUALITY CONTROL REQUIREMENTS

The QA officers at each laboratory will be responsible for conducting and reporting corrective actions if problems arise during the course of laboratory analytical procedures.

10.1 Quality Assurance Indicators

The overall QA objective for this assessment is to develop and implement procedures for sampling, COC, laboratory analysis, instrument calibration, data reduction and reporting, internal QC, preventive maintenance, and corrective action such that valid data will be generated for site assessment purposes. These procedures are presented or referenced in subsequent sections of this QAPP.

QA objectives are generally defined in terms of five parameters:

1. Representativeness
2. Comparability
3. Completeness
4. Precision
5. Accuracy
6. Sensitivity

Each parameter is defined below. Specific objectives for this assessment are set forth in other sections of this QAPP as referenced below.

10.1.1 Representativeness

Representativeness is the degree to which sample data accurately and precisely represent site conditions, and is dependent on sampling and analytical variability and the variability (or homogeneity) of the site. The site assessment has been designed to assess the presence of the chemical constituents and supplemental parameters at the time of sampling and throughout the study area. The SAP and this QAPP present field sampling methodologies and laboratory analytical methodologies. The use of the prescribed field and laboratory analytical methods with associated holding times and preservation requirements are intended to provide representative data.

10.1.2 Comparability

Comparability is the degree of confidence with which one dataset can be compared to another. Comparability between phases of the current assessment, and to the extent possible, between new and existing data will be maintained through consistent use of the sampling and analytical methodologies set forth in this QAPP and the SAP through stringent application of established QA/QC procedures and through utilization of appropriately trained personnel.

10.1.3 Completeness

Completeness is defined as a measure of the amount of valid data obtained from an event and/or investigation compared to the total amount that was obtained. This will be determined upon final assessment of the analytical results. Completeness is also a measure of how many data were collected as compared to the total amount that were planned to be collected.

10.1.4 Precision

Precision is a measure of the reproducibility of sample results. The goal is to maintain a level of analytical precision consistent with the objectives of the site assessment. To maximize precision, sampling and analytical procedures will be strictly followed; work will adhere to established protocols presented in this QAPP and SAP. Checks for analytical precision will include the analysis of MS/MSD pairs (as applicable to the method), laboratory duplicates, and field duplicates. Field measurement precision will be monitored by obtaining duplicate field measurements.

10.1.5 Accuracy

Accuracy is a measure of how close a measured result is to the true value. Recovery of reference standards, MSs, laboratory control standards, and surrogate standards, where applicable to the method, will be used to assess the accuracy of the analytical data.

10.1.6 Sensitivity

Sensitivity is defined as the ability of the method or instrument to detect the constituent of concern and other target compounds at the level of interest. The method detection limit (MDL) is defined as the minimum concentration of a substance that can be identified, measured, and reported with a 99% confidence that the analyte concentration is greater than zero and is determined from repeated analysis of a sample in a given matrix containing the analyte. MDLs have been determined as required in Title 40 of the Code of Federal Regulations Part 136B. The reporting limit (RL) is greater than or equal to the lowest standard used to establish the calibration curve. The RLs for this investigation are generally at least 3 times greater than the MDL. Results greater than the MDL and less than the RL will be qualified estimated (J) by the laboratory. For radiochemical analyses in water, the detection limit shall be that activity concentration, which can be counted with a precision of plus or minus 100% at the 95% confidence level.

10.2 Field Quality Control Checks

10.2.1 Sample Containers

Containers will be supplied by the laboratory and are pre-cleaned.

10.2.2 Field Duplicates

Field duplicates will be collected to verify the reproducibility of the sampling methods. In general, field duplicates will be analyzed at a 5% frequency (one in every 20 samples) for the chemical constituents. The SAP provides the frequency at which field duplicates will be prepared for this investigation.

10.2.3 Equipment Blanks

Equipment blanks are used to monitor the cleanliness of the sampling equipment and the effectiveness of the decontamination procedures. Equipment blanks will be prepared and submitted for analysis at a 5% frequency (one in every 20 samples) for relevant sample collection activities. Equipment blanks will not be collected for soil samples if the soil will be accessed directly using single-use, sterile, disposable scoops and placed directly into the laboratory-supplied sample container; if reusable equipment is used, an equipment blank will be collected by pouring laboratory-supplied water over the decontaminated equipment and submitting to the laboratory for analysis. Equipment blanks for water will be prepared by filling sample containers with analyte-free water (supplied by the laboratory) or purchased from a laboratory supply vendor that has been routed through a cleaned sampling device. When dedicated sampling devices are used or sample containers are used to collect the samples, equipment blanks will not be necessary.

10.2.4 Field Blanks – Clean Water Source

The clean water source blank (field blank) sample is a sample of the water source used for final equipment cleaning/rinsing and is collected and analyzed to assess the integrity of the water source. One field blank sample will be collected for each source of clean water used during the sampling event. The field blank sample will be collected from the water source in appropriate sample containers provided by the laboratory. When dedicated sampling devices or sample containers are used to collect the samples, field blank samples will not be necessary.

10.3 Analytical Laboratory Quality Control Checks

Internal laboratory QC checks will be used to monitor data integrity. These checks may include method blanks, MS/MSD pairs, LCSs, laboratory duplicates, internal standards, and calibration standards. Where applicable, laboratory control charts will be used to determine long-term instrument trends. Control limits for the QC samples will be consistent with the analytical method requirements and/or laboratory generated limits.

10.3.1 Method Blanks

Sources of contamination in the analytical process, whether specific analyses or interferences, must be identified, isolated, and corrected. The method blank is useful in identifying possible sources of contamination within the analytical process. For this reason, it is necessary that the method blank be initiated at the beginning of the analytical process (where applicable to the method) and encompasses all aspects of the analytical work. As such, the method blank would assist in accounting for any potential contamination attributable to glassware, reagents, instrumentation, or other sources that could affect

sample analysis. One method blank will be analyzed with each analytical series associated with no more than 20 samples. Ideally, method blanks should not contain any detected analytes above the RL.

10.3.2 Matrix Spike/Matrix Spike Duplicates

Where applicable to the method, MS/MSDs will be used to measure the accuracy of analyte recovery from the sample matrices and will be site-specific. MS/MSD pairs will be analyzed at a 5% frequency (every 20 samples).

When MS recoveries are outside QC limits, associated LCS recoveries will be evaluated, as applicable, to attempt to verify the reason for the deviation and determine the effect on the reported sample results. The SAP provides the frequency at which MS/MSD pairs will be collected for this field investigation.

10.3.3 Laboratory Control Samples

Where applicable to the method, LCSs are standards of known concentration and are independent in origin from the calibration standards. The intent of LCS analysis is to provide insight into the analytical proficiency within an analytical series. This includes preparation of calibration standards, validity of calibration, sample preparation, instrument setup, and the premises inherent in quantitation. Reference standards will be analyzed at the frequencies specified within the analytical methods.

10.3.4 Laboratory Duplicates

Where applicable to the method, laboratory duplicates will be analyzed to assess laboratory precision. Laboratory duplicates are defined as a separate aliquot of an individual sample that is analyzed as a separate sample. For this Site, when MS/MSD pairs are not performed for certain methods, a site-specific laboratory duplicate will be requested. In this case, laboratory duplicates will be requested at a 5% frequency (every 20 samples).

10.3.5 Calibration Standards

Calibration check standards analyzed within a particular analytical series provide insight regarding instrument stability. A calibration check standard will be analyzed, where applicable to the method, at the beginning and end of an analytical series, or periodically throughout a series containing a large number of samples, per method requirements.

In general, calibration check standards will be analyzed after every 12 hours or more frequently, as specified in the applicable analytical method. If results of the calibration check standard exceed specified tolerances, samples analyzed since the last acceptable calibration check standard will be re-analyzed.

Laboratory instrument calibration standards will be selected utilizing the guidance provided in the analytical methods as summarized in Section 8.2.

10.4 Data Precision Assessment Procedures

Field precision is difficult to measure because of temporal variations in field parameters. However, precision will be controlled through the use of experienced field personnel, properly calibrated meters,

and duplicate field measurements. Field duplicates will be used to assess precision for the entire measurement system, including sampling, handling, shipping, storage, preparation, and analysis.

Laboratory data precision for analyses will be monitored through the use of MSDs, laboratory duplicates, and field duplicates, where applicable to the method. The RPD for MSD and laboratory duplicate pairs will be within laboratory-generated control limits or as specified by the analytical method. For field duplicate analyses, RPD criteria are $\leq 50\%$ for soil samples and $\leq 35\%$ for water samples.

The precision of data will be measured by calculation of the RPD by the following equation:

$$RPD = \frac{(A - B)}{\frac{(A + B)}{2}} * 100$$

Where:

A = Analytical result from one of two duplicate measurements

B = Analytical result from the second measurement

10.5 Data Accuracy Assessment Procedures

The accuracy of field measurements will be controlled by experienced field personnel, properly calibrated field meters, and adherence to established protocols. The accuracy of field meters will be assessed by review of calibration and maintenance logs.

Where applicable to the method, laboratory accuracy will be assessed using MSs, LCS, internal standards, and reference standards. Where available and appropriate, QA performance standards will be analyzed periodically to assess laboratory accuracy. Recoveries will be assessed against laboratory established limits or as specified in the analytical method. Accuracy will be calculated in terms of percent recovery as follows:

$$\%Recovery = \frac{(A - X)}{B} * 100$$

Where:

A = Value measured in spiked sample or standard

X = Value measured in original sample

B = True value of amount added to sample or true value of standard

11 ASSESSMENT AND RESPONSE ACTIONS

If necessary, performance and systems assessments will be completed in the field and the laboratory, as described below.

11.1 Field Performance

The following field performance reviews may be completed during this project.

The Arcadis Technical Lead will monitor field performance. Field performance summaries will contain an evaluation of field activities to verify that the activities are performed according to established protocols. Field performance reviews may be performed by the Arcadis QAM. The reviewer(s) will review field reports and communicate concerns to the Arcadis PM and/or Technical Lead and/or HMC, as appropriate.

Observations made during field performance reviews and any recommended changes/deviations to the field procedures will be recorded and documented. The observations and any recommendations will be distributed to the HMC Project Team, as appropriate.

In addition, actual QA/QC activities completed will be compared against reviews of QA/QC activities described in this QAPP. The Arcadis QAM will periodically confirm that work is being performed consistently with this QAPP.

11.2 Corrective Action

Corrective actions are required when field or analytical data are not within the objectives specified in this QAPP or the SAP. Corrective actions include procedures to promptly investigate, document, evaluate, and correct data collection and/or analytical procedures. Field and laboratory corrective action procedures for the assessment are described below.

11.2.1 Field Procedures

If, during field work, a condition is noted by the field crew that would have an adverse effect on data quality, corrective action will be taken so as not to repeat this condition. Condition identification, cause, and corrective action implemented by the field personnel will be documented and reported to the Arcadis Technical Lead and QAM. The Arcadis QAM or designee will be responsible for follow-up and acceptance of corrective actions.

Examples of situations that would require corrective actions are provided below:

- Protocols as defined by the QAPP or SAP have not been followed
- Equipment is not in proper working order or properly calibrated
- QC requirements have not been met

Project personnel will continuously monitor ongoing work performance in the normal course of daily responsibilities.

11.2.2 Laboratory Procedures

In the laboratory, when a condition is noted to have an adverse effect on data quality, corrective action will be taken so as not to repeat this condition. Condition identification, cause, and corrective action to be taken will be documented, and reported to the appropriate laboratory PM and QAM. If previously reported data are affected by a situation requiring correction or if the corrective action impacts a project budget or schedule, the laboratory PM and QAM will contact the Arcadis PM, Technical Lead, or QAM.

12 DATA REDUCTION AND REVIEW

12.1 General

After field and laboratory data are obtained, the data will be subjected to the following:

- Reduction, or manipulation mathematically or otherwise into meaningful and useful forms
- Data verification check between sample results contained in the pdf of the laboratory report and EDDs (where provided) will be performed at a rate of 10% by the Arcadis QAM or designee
- Tier I data validation on Level 2 reports
- Organization, interpretation, and reporting

12.2 Field Data Reduction and Review

12.2.1 Field Data Reduction

Information collected in the field through visual observation, manual measurement, and/or field instrumentation will be recorded in field log books, data sheets, and/or on forms as described above and in the SAP. Such data will be reviewed by the Arcadis QAM or designee for adherence to the SAP and this QAPP and for consistency. Concerns identified as a result of this review will be discussed with field personnel, corrected if possible, and (as necessary) incorporated into the data evaluation process.

12.2.2 Field Data Review

Field data calculations, transfers, and interpretations will be conducted by the field personnel and reviewed for accuracy by the Arcadis QAM or designee. Logs and documents will be checked for:

- General completeness
- Readability
- Usage of appropriate procedures
- Appropriate instrument calibration and maintenance
- Reasonableness in comparison to present and past data collected
- Correct sample locations
- Correct calculations and interpretations

12.3 Laboratory Data Reduction and Review

12.3.1 Laboratory Data Reduction

The calculations used for data reduction will be in accordance with the analytical methods. Whenever possible, analytical data will be transferred directly from the instrument to a computerized data system. Raw data will be entered into permanently bound laboratory notebooks. The data entered must be sufficient to document all factors used to arrive at the reported value.

13 DATA VALIDATION

Data validation will be conducted, as outlined in USEPA Guidance on Environmental Data Verification and Data Validation EPA QA/G-8 (USEPA 2002).

Data validation is a standardized review process for judging the analytical quality and usefulness of a discrete set of chemical data and is necessary to ensure that data of known and documented quality are used in making environmental decisions that meet the DQOs of the Site. Data validation is a systematic process that compares a body of data to the requirements in a set of documented acceptance criteria to ascertain its completeness, correctness, and consistency.

13.1 Data Validation Process

All data generated will be validated using USEPA National Functional Guidelines for Inorganic Superfund Methods Data Review, EPA 540-R-2017-001, January 2017 (with reference to the historical USEPA Contract Laboratory Program National Functional Guidelines for Inorganic Data Review, OSWER 9240.1-45, October 2004, as appropriate) upon receipt of all of the laboratory-generated data, where appropriate. These procedures and criteria may be modified, as necessary, to address project-specific and method-specific criteria, control limits, and procedures. Data validation will consist of data screening, checking, and reviewing to document analytical data quality and to determine whether the quality is sufficient to meet the DQOs.

Upon receipt of all laboratory data, the following validation procedures will be executed as a Tier I level validation:

- Evaluate completeness of data package.
- Verify that field COC forms were completed and that samples were handled properly.
- Verify that holding times were met for each parameter. Holding time exceedances, if they occur, will be documented. Data for all samples exceeding holding time requirements will be flagged as either estimated or rejected. The decision as to which qualifier is more appropriate will be made on a case-by-case basis.
- Verify that parameters were analyzed according to the methods specified.
- Review QA/QC data [i.e., confirm that laboratory QC checks (LCS, MS/MSD, laboratory duplicates) were analyzed for the required number of samples as specified in the method and that the recoveries and RPDs were within the laboratory-generated or method-specified control limit].
- Review blank results (i.e., method blanks, instrument calibration blanks, field blanks, and equipment blanks) and evaluate potential impacts to field sample results.
- Investigate all anomalies identified during review. When anomalies are identified, they will be discussed with the Arcadis PM and Technical Lead and/or laboratory PM, as appropriate.

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Deficiencies discovered as a result of the data review, as well as the corrective actions implemented in response, will be documented and submitted in the form of a written report addressing the following topics, as applicable to each method:

- Assessment of the data package
- Description of any protocol deviations
- Assessment of any compromised data
- Overall appraisal of the analytical data
- Table of site name, sample quantities, matrix, and fractions analyzed

It should be noted that qualified results do not necessarily invalidate data. The goal to produce the best possible data does not necessarily mean that data must be produced without QC qualifiers. Qualified data can provide useful information.

During the review process, laboratory qualified and unqualified data are verified against the supporting documentation. Based on this evaluation, qualifier codes may be added, deleted, or modified by the data reviewer. Results will be qualified in accordance with National Functional Guidelines (USEPA 2017).

Resolution of issues regarding laboratory performance or deliverables will be handled between the laboratory and the data validator. Suggestions for re-analysis may be made by the laboratory PM or QAM at this point.

Data validation reports will be kept in electronic format (pdf) at the environmental consultant's office.

14 RECONCILIATION WITH USER REQUIREMENTS

Data results will be examined to determine the performance that was achieved for each data usability criterion. The performance will then be compared with the project objectives and DQOs. Deviations from objectives will be noted. Additional action may be warranted when performance does not meet performance objectives for critical data. Options for corrective action relating to incomplete information, questionable results, or inconsistent data may include any or all of the following:

- Retrieval of missing information
- Request for additional explanation or clarification
- Reanalysis of sample from extract (when appropriate)
- Re-calculation or reinterpretation of results by the laboratory

These actions may improve the data quality, reduce uncertainty, and eliminate the need to qualify or reject data.

If these actions do not improve the data quality to an acceptable level, the following additional actions may be taken:

- Extrapolation of missing data from existing data points
- Use of historical data
- Evaluation of the critical/non-critical nature of the sample

If the data gap cannot be resolved by these actions, an evaluation of the data bias and potential for false negatives and positives can be performed. If the resultant uncertainty level is unacceptable, additional sample collection and analysis may be required.

15 REFERENCES

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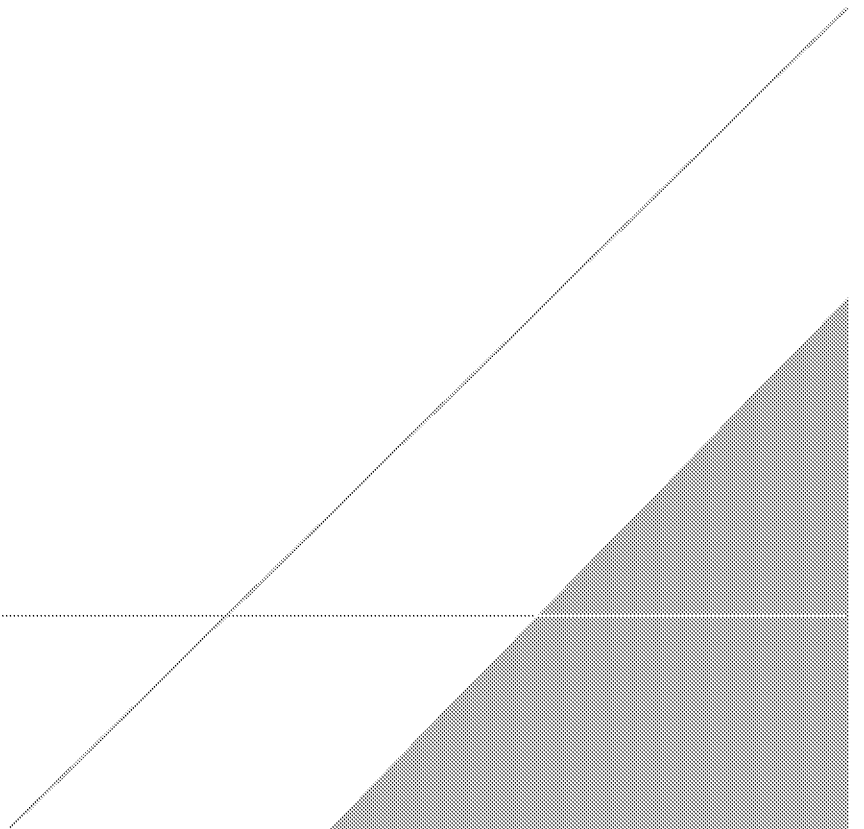
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SAP

APPENDIX B

Field Forms



Geophysical Logging Field Form



Design & Consultancy
for natural and
built assets

All Personnel Present: _____

Date/Time: _____

Site: _____

Weather Conditions: _____

Location: _____

Well ID: _____

Well Type: ☐ Monitoring ☐ Other: _____

Well Finish: ☐ Stick Up ☐ Flush Mount

Measuring Pt: ☐ Top of Casing ☐ Other (specify): _____

Total Depth (ft bgs): _____ Screened Interval (ft bgs): _____

Well Casing: Diameter (in.): _____ Material: _____

Well Screen: Diameter (in.): _____

Static depth to water: _____ ft btoc

Geophysical Tool	Make/Model	Calibrated?	Time in	Time out	Logging Speed	Depth Deployed (ft bTOC)

Casing condition: _____

Notes/Observations: (e.g. reproducibility of data acquisition, preliminary results, decontamination procedures, picture #s)

SAP

APPENDIX C

Standard Operating Procedures



Field Log Book Entries

Rev. #: 0

Rev Date: 11 August 2009

I. Scope and Application

This ARCADIS Standard Operating Procedure covers the entries needed in a field log book for environmental investigations.

This SOP does not address all of the entries that may be needed for a specific project, and does not address health and safety, equipment decontamination, field parameter measurements, sample preservation, chain-of-custody, or laboratory analysis. For direction on requirements in these areas, refer to other ARCADIS SOPs, the project work plans including the quality assurance project plan, sampling plan, and health and safety plan, as appropriate.

II. Personnel Qualifications

ARCADIS personnel participating in fieldwork and making entries into the field log book should have a minimum of one (1) year of field experience (or be under the supervision and accompanied in the field by someone who does) and current health and safety training including 40-hour HAZWOPER training, site supervisor training, site-specific training, first aid, and CPR, as needed. Field personnel will also be compliant with client-specific training requirements. In addition, ARCADIS field sampling personnel will be versed in the relevant SOPs and possess the required skills and experience necessary to successfully complete the desired field work.

III. Equipment List

- Field Log Book
- Ball point (medium point) pen with blue or black ink (black preferred). A fine point Sharpie pen may be used if the ink does not bleed through the page and become visible on back side of the page. If weather conditions prevent the use of a pen, indicate so in the log and use an alternate writing instrument .
- Zip-lock baggie or other weather-proof container to protect the field log book from the elements.

IV. Cautions

All entries in the field log must be legible and archivable. Do not leave the field log book exposed to the elements or other conditions that might moisten the pages and smear/dissolve the entries. When not in the field, the log book should be stored in a location that is easily accessible to field crews.

V. Health and Safety Considerations

ARCADIS field personnel will be familiar and compliant with Client-specific health and safety requirements.

VI. Procedure

- Print legibly. Do not use cursive writing.
- The name of the project, project number and project location should be written in indelible ink on the outside of the field log book.
- On the inside of the front cover, write "If Found, Please Return to ARCADIS" and include the appropriate address and phone number, the name of the person to which the book is assigned, and the name of the project manager.
- Reserve the first page of the book for a Table of Contents.
- Reserve the last five (5) pages of the book for important contacts, notes, reminders, etc.
- Each day of field work, the following should be recorded in the field log book as applicable:
 - a) Project Name
 - b) Date and time arrived
 - c) Work Site Location
 - d) Names of people on-site related to the project including ARCADIS employees, visitors, subcontractor employees, agency personnel, client representative, etc.
 - e) Describe the work to be performed briefly, and list the equipment on-site
 - f) Indicate the health and safety (H&S) level to be used
 - g) Record instrument calibrations and checks
 - h) Record time and general content of H&S briefing
 - i) Describe the weather conditions, including temperature, precipitation, and wind speed and direction
 - j) List periodic time entries in the far left hand column of each page
 - k) Minimize unused space on each page
- The tailgate meeting must be recorded in the log book and the tailgate form completed. If H&S monitoring is performed, record the time and results of initial and followup monitoring.

- Note factual observations including collection of QA/QC samples, delays, well damage, accidents, work plan deviations, instrument problems, and problem resolutions.
- Describe work performed and how documented such as photographs, sample core logs, water sampling logs, etc.
- Describe bases for field decisions including pertinent conversations with visitors, regulators, or project personnel.
- Note final instrument calibrations and checks.
- Sign the log book at the end of each day at a minimum. Draw a line to the end of the page to indicate no further entries on that page. Sign the bottom of each page if possible.
- If an entry to the log book is changed, strike out the deleted text or item with a single line such that the entry remains legible, and initial and date the change. Such changes should only be made by the same person that made the initial entry.
- Field log book entries must be made in the field at the site, not at a later time at a different location. Supplemental entries to the log book may be made at a later date. The supplemental entry must be clearly identified as such and the entry must be signed and dated as described in this SOP.
- Problems noted in the field log book must be brought to the attention of the project manager and task manager in a timely fashion. Problems may be reported in person, on the telephone, or in a written daily log form. If daily logs are prepared and you will not be able to personally give the daily log to the project manager, send the daily log via FAX or overnight courier to the project manager and task manager.

VII. Waste Management

Investigation-derived waste will be managed as described in the Investigation-Derived Waste Handling and Storage SOP. A drum/waste inventory should be maintained on a pre-designated page in the field log book.

VIII. Data Recording and Management

Each page of the field log book should be scanned for electronic/digital archiving at periodic intervals. This will ensure that copies of the field notes are available in the event the field book is lost or damaged, and that field data can be easily disseminated to others without the risk of physically sending the field log book. Field log books that are full should be archived with the project files, and readily retrievable.

IX. Quality Assurance

Be mindful that the field log book may be produced in court. All entries should be legible (as discussed above). Entries should also be in English, unless working in a country where English is not the predominant language or you are directed otherwise by the project manager.

X. References

Not Applicable

Water Level Measurement

Rev. #: 2

Rev Date: February 24, 2011

I. Scope and Application

The objective of this Standard Operating Procedure (SOP) is to describe procedures to measure and record groundwater and surface-water elevations. Water levels may be measured using an electronic water-level probe, oil-water level indicator, or a pressure transducer from established reference points (e.g. top of casing). Reference points will be surveyed to evaluate fluid elevations relative to mean sea level (msl). This SOP describes the equipment, field procedures, materials, and documentation procedures to measure and record groundwater and surface-water elevations using the aforementioned equipment.

This is a standard (i.e., typically applicable) operating procedure which may be varied or changed as required, dependent upon site conditions, equipment limitations, or limitations imposed by the procedure. The ultimate procedure employed will be documented in the project work plans or reports.

II. Personnel Qualifications

ARCADIS field sampling personnel will have current health and safety training including 40-hour HAZWOPER training, site supervisor training, site-specific training, first aid, and CPR, as needed. In addition, ARCADIS field sampling personnel will be versed in the relevant SOPs and possess the required skills and experience necessary to successfully complete the desired field work.

III. Equipment List

The following materials, as required, shall be available during water level measurements:

- Appropriate personal protective equipment as specified in the Site Health and Safety Plan
- Equipment decontamination supplies
- Electronic water-level indicator
- Electronic oil-water level indicator
- Mini-Troll® or Troll® pressure transducer
- In-Situ™ data logger

- Laptop computer with the Win-Situ software package installed
- Photoionization detector (PID) and/or organic vapor analyzer
- Non-phosphate laboratory soap (Alconox or equivalent)
- Deionized/distilled water
- 150-foot measuring tape
- Solvent (methanol/acetone) rinse
- Portable containers
- Hacksaw
- Pliers
- Plastic sheeting
- “Write-in-the-Rain” Field logbook and or PDA (Personal Digital Assistant)
- Indelible ink pen.

IV. Cautions

Electronic water-level probes and oil-water interface probes can sometimes produce false-positive readings. For example, if the inside surface of the well has condensation above the water level, then an electronic water-level probe may produce a signal by contacting the side of the well rather than the true water level in the well. To produce reliable data, the electronic water level probe and/or interface probe should be raised and lowered several times at the approximate depth where the instrument produces a tone indicating a fluid interface to verify consistent, repeatable results.

The graduated tape or cable with depth markings is designed to indicate the depth of the electronic sensor that detects the fluid interface, but not the depth of the bottom of the instrument. When using these devices to measure the total well depth, the additional length of the instrument below the electronic sensor must be added to the apparent well depth reading, as observed on the tape or cable of the instrument, to obtain the true total depth of the well. If the depth markings on the tape or cable are

worn or otherwise difficult to read, extra care must be taken in obtaining the depth readings.

V. Health and Safety Considerations

The HASP will be followed, as appropriate, to ensure the safety of field personnel. Access to wells may expose field personnel to hazardous materials such as contaminated groundwater or oil. Other potential hazards include stinging insects that may inhabit well heads, other biologic hazards, and potentially the use of sharp cutting tools (scissors, knife). Appropriate personal protective equipment (PPE) will be worn during these activities. Field personnel will thoroughly review client-specific health and safety requirements, which may preclude the use of fixed/folding-blade knives.

VI. Procedure

Electronic Water-Level Indicators and Oil-Water Indicators

Calibration procedures and groundwater level measurement procedures for electronic water-level indicators and oil-water indicators are described in the sections below.

Calibration Procedures

The indicator probe will be tested to verify that the meter has been correctly calibrated by the manufacturer. The following steps will be used to verify the accuracy of the indicator:

1. Measure the lengths between each increment marker on the indicator with a measuring tape. The appropriate length of indicator measuring tape, suitable to cover the depth range for the wells of interest, will be checked for accuracy.
2. If the indicator measuring tape is inaccurate, the probe will be sent back to the manufacturer.
3. Equipment calibration will be recorded in the field logbook and/or PDA.

Groundwater Level Measurement Procedures

A detailed procedure for obtaining water elevations will be as follows:

1. Identify site and monitoring well number in field notebook along with date, time, personnel and weather conditions using indelible ink.

2. Use safety equipment as specified in the Health and Safety Plan.
3. Decontaminate the indicator probe and tape in accordance with the appropriate cleaning procedures.
4. Place clean plastic sheeting on the ground next to the well.
5. Unlock and open the monitoring well cover while standing upwind from the well.
6. Measure the volatile organics present in the monitoring well head space with a PID and record the PID reading in the field logbook.
7. Allow the water level in the well to equilibrate with atmospheric pressure for a few minutes. Locate a measuring reference point on the monitoring well casing. If one is not found, create a reference point by notching the highest point on the inner casing (or outer if an inner casing is not present) with a hacksaw. All downhole measurements will be taken from the reference point. Document the creation of any new reference point or alteration of the existing reference point.
8. Measure to the nearest 0.01 foot and record the height of the inner and outer casing from reference point to ground level.
9. Slowly lower the level indicator probe until it touches the bottom of the well. Record the total depth of the well from the top of the inner casing (or outer casing if inner casing is not present). Measure depth to water level as the probe is drawn back up through the water column. If used to measure the level of surface water, slowly lower from the surveyed reference point, as appropriate. Double check all measurements and record depths to the nearest 0.01 foot.
10. Decontaminate the instrument using appropriate cleaning procedures.
11. Lock the well when all activities are completed.

Pressure Transducers

The detailed procedure for obtaining water elevations using a Mini-Troll® or Troll® pressure transducer with an In-Situ™ data logger and the Win-Situ software package will be as follows:

Setup Procedures

1. Connect the Mini-Troll® or Troll® transducer to a laptop computer serial port.

2. Open the Win-Situ software package on the laptop computer.
3. Verify that the Win-Situ software recognizes the transducer.
4. Synchronize the clock on the laptop computer with that of the transducer.
5. Add a test to the transducer and input the specifications of the test (e.g., frequency of data collection, start data collection).
6. Disconnect the transducer from the laptop computer, and prepare the transducer for field deployment.

Field Procedures

1. Decontaminate all equipment entering the monitoring well using appropriate cleaning procedures.
2. Connect transducer to laptop computer, and start the Win-Situ program.
3. Lower the transducer gently below the water table or surface-water level.
4. Take a water level reading from the transducer using the Win-Situ software package. Lift the transducer approximately 1-foot, and verify the transducer response on the Win-Situ program (i.e. depth to water should be 1-foot less).
5. Upon verification, set the transducer to the desired depth. Position the instrument below the lowest anticipated water level, but not so low that its range will be exceeded at the highest anticipated water level. The maximum operating depth below water is equal to 2.31 feet times the psi rating of the transducer (e.g., 23.1 feet for a 10 psi transducer).
6. Secure the cable at the well head or fixed object adjacent to surface-water body to prevent drift and movement.
7. Obtain a manual water-level reading using the procedure noted above, and record the measurement in the field notebook or PDA.
8. Set reference point (e.g. depth to water, groundwater elevation) and input it into the Win-Situ software package.

9. Periodically download data and collect additional manual depth-to-water measurements using the same water-level or oil-water indicator probe used during the equipment setup to verify the accuracy of the transducer.

VII. Waste Management

Decontamination fluids, PPE, and other disposable equipment will be properly stored on site in labeled containers and disposed of properly. Be certain that waste containers are properly labeled and documented in the field log book. Review appropriate waste management SOPs, which may be state- or client-specific.

VIII. Data Recording and Management

Groundwater level measurements should be documented in the field logbook and/or PDA. The following information will be documented in the field logbook:

- Sample identification
- Measurement time
- Total well depth
- Depth to water

Groundwater elevations recorded using a Mini-Troll® or Troll® pressure transducer with an In-Situ™ data logger and the Win-Situ software package will be downloaded and stored in the central project file.

IX. Quality Assurance

As described in the detailed procedure, the electronic water-level meter and/or oil-water interface probe will be calibrated prior to use versus an engineer's rule to ensure accurate length demarcations on the tape or cable. Fluid interface measurements will be verified by gently raising and lowering the instrument through each interface to confirm repeatable results.

X. References

No literature references are required for this SOP.

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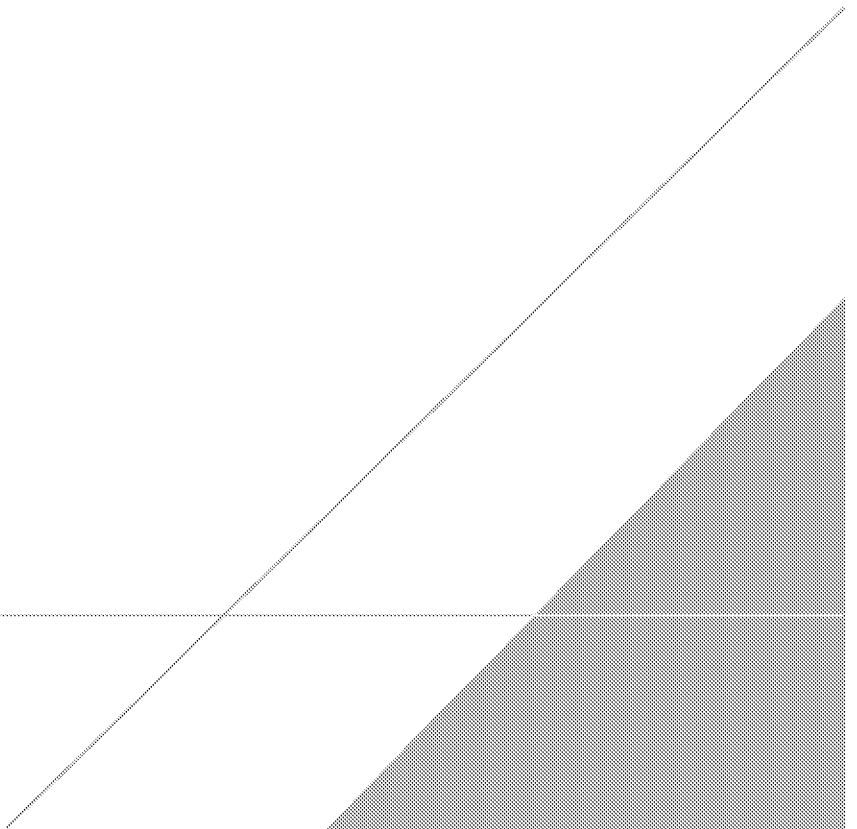
Fax 720 344 3535

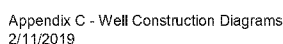
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WORK PLAN

APPENDIX B

Proposed Well Construction Diagrams







1. Exact bore completion depth, screen length and placement to be determined based on lithology at each well location
2. Soil logged in accordance with ASTM designation D2488
3. Well to be surveyed by licensed surveyor
4. Plastic centralizers to be placed at bottom and top of screen
5. Grout placed with tremie pipe and positive displacement
6. Plinth sloped to drain water away from well
7. Anticipated depth to water 45 feet below ground surface

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Message

From: Lattin, Daniel [dlattin@barrick.com]
Sent: 2/13/2019 11:33:43 PM
To: Purcell, Mark [purcell.mark@epa.gov]
CC: Travis, Pamela [Travis.Pamela@epa.gov]; Shade, Kevin [Shade.Kevin@epa.gov]; Kevin Murray (krmurray@hollandhart.com) [krmurray@hollandhart.com]; Malone, Patrick [pmalone@barrick.com]; McCarthy, Michael [mmccarthy@barrick.com]; Wohlford, Tom [twohlford@barrick.com]; Ulrich, Shannon [Shannon.Ulrich@arcadis.com]; Burton, Clark [CBurton@barrick.com]; Vollbrecht, Kurt, NMENV [kurt.vollbrecht@state.nm.us]
Subject: GRP BG - DRAFT 2019 Background Study Work Plan
Attachments: 20190213 GRP BG - DRAFT 2019 Background Study Work Plan.pdf

Mark,

As indicated during the February 12, 2018 call with EPA and NMED, Homestake is providing a DRAFT 2019 Grants Reclamation Project Background Investigation Work Plan. Figure 4 shows the proposed geophysical assessments and borehole locations.

Regards,

BARRICK

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Identifying natural and anthropogenic variability of uranium at the well scale, Homestake Superfund site, near Milan, New Mexico, USA

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Abstract

The San Mateo Creek Basin in New Mexico, USA is located within the Grants Mineral Belt—an area with numerous uranium (U) ore deposits, mines, and milling operations. Six monitoring wells set in an alluvial aquifer near the Homestake Mining Co. Superfund site in the lower San Mateo Creek Basin were logged with a suite of borehole geophysical tools including spectral gamma-ray (SGR), vertically profiled with passive samplers for U and selenium (Se) concentrations, and purged sampled for same constituents. The integrated approach allowed for an assessment on the role of heterogeneity (both physical and chemical) in determining U concentrations in groundwater. Uranium, as measured with SGR logging, is ubiquitous in the alluvial aquifer and the underlying Chinle Group. Aqueous U concentrations appear to be inversely related to thorium (Th) concentrations, as measured by the SGR log, indicating the possibility that U is bound in or adsorbed to clays in the aquifer. The stratigraphy of the alluvium likely plays a role in elevated concentrations of aqueous U. Interbedded clay and sand layers allow for the mobilization of U in oxic sandy layers from U adsorbed in sediments in reduced clay layers. The stratigraphy also plays a role in the degree of mixing of groundwater in the formation and well. Mixing can obscure the ability to identify U sources. Mixing is exacerbated by the relatively long screens (> 20 ft long or > 6.1 m) of the monitoring wells.

Keywords Spectral gamma-ray · Passive samplers · Micropurge · Uranium · Selenium

Introduction

The natural physical and chemical heterogeneity of a groundwater-flow system can complicate the identification of ambient concentrations of uranium (U). Further, the use of monitoring wells with long screens (> 20 ft or > 6.1 m) for sampling can cause mixing of groundwater from different

hydrogeologic units and formations, each with potentially unique U concentrations and water types.

While heterogeneity is a factor, variable sources of U, such as natural and anthropogenic (enrichments caused by mining or other activities), are also problematic in distinguishing natural background concentrations of U. Activities such as mining and milling can cause enrichment of U as evidenced by elevated aqueous U concentrations in groundwater, association with co-contaminants such as molybdenum (Mo), selenium (Se), and alterations to the common U isotopes of ²³⁴U, ²³⁵U, and ²³⁸U (Zielinski et al. 1997). When there are multiple mining and milling sources, distinguishing between these anthropogenically enriched sources is further complicated.

Elevated concentrations of U and co-occurring constituents, such as Se and Mo, in groundwater have been detected at and surrounding the Homestake Mining Co. Superfund site (Site) near the village of Milan (hereafter referred to as Milan), New Mexico (Fig. 1a) (Hydro-Engineering 2001). The groundwater may be affected by undisturbed ore deposits (natural sources) and mining or milling activities

Electronic supplementary material The online version of this article (<https://doi.org/10.1007/s12665-019-8049-y>) contains supplementary material, which is available to authorized users.

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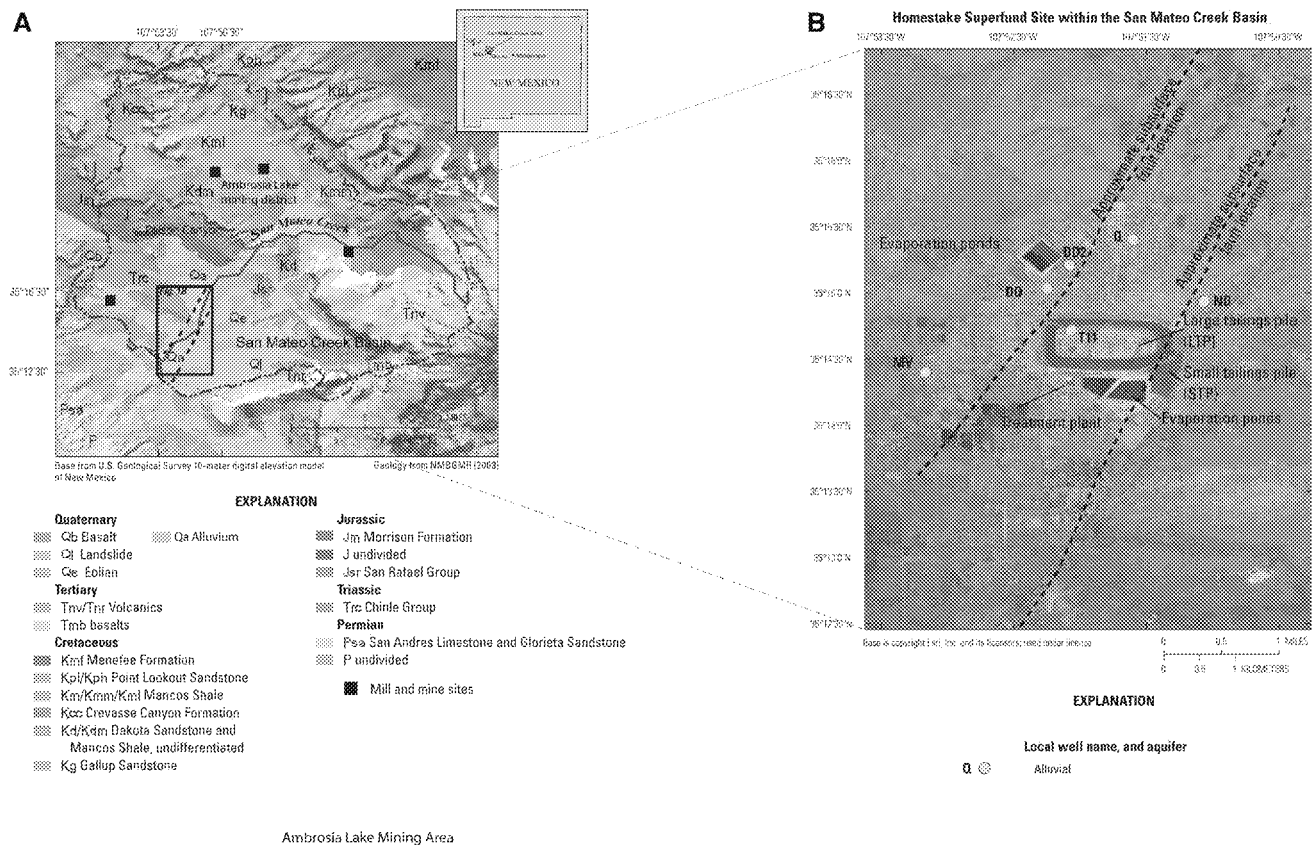


Fig. 1 The location of study area showing the San Mateo Creek Basin, and logged and sampled wells, Homestake Superfund site, near Milan, New Mexico, USA (The Grants Mineral Belt covers much of **a**)

(anthropogenic sources). Locally, two tailings piles, large (LTP) and small (Fig. 1b), located on the Site, likely affect the water quality in adjacent aquifers. Regionally, dewatering of uranium mines in the upper San Mateo Creek Basin and the Ambrosia Lake mining district (Fig. 1a), located north of the site, have led to the contamination of downstream sediments from stream transport, and downgradient groundwater in the alluvial and underlying rock aquifers (via faults) (Gallaher and Goad 1981; Schoeppner 2008) because mine waters were discharged into natural waterways without treatment (Langman et al. 2012). Uranium and Mo are considered the most mobile elements from U mill sites and Se is also associated with U ore (Morrison and Spangler 1992). Selenium concentrations related to the Poison Canyon area, located upgradient (northwest) of the Site, are generally high (Gallaher and Cary 1986) (Fig. 1a). To the northeast of the Site, solid U concentrations from surficial material are low and indicate a naturally low U source rock (NURE 2017).

This paper focuses on the role that physical and chemical heterogeneity plays in the variability of U concentrations in groundwater of the alluvial aquifer at the Site within the framework of distinguishing natural and anthropogenic sources of U. This work is part of a larger study to

differentiate chemical signatures in the water with one or more U sources using geochemical and isotopic analyses (Harte et al. 2018b).

Site description

The Site received processed raw U ore material from external sites starting in 1958; from 1958 to 1990 milling activities continued. Other contaminants of concern associated with U include thorium-230, radium-226, radium-228, Se, Mo, sulfate, and dissolved solids. The LTP was constructed starting in the early 1960s without a liner, and processed materials, including wastewater as a transporting device, were deposited onto the LTP. Waste water infiltrated into a surficial alluvial aquifer from both the LTP and a small tailings pile (STP) [U.S. Environmental Protection Agency (EPA) 2010] (Fig. 1b). Beginning in 1977 and until the present, various levels of remedial activities have been initiated to contain the spread of a U plume emanating from the site. Activities have included the flushing of the tailings from 2000 to 2015 with uncontaminated groundwater from a lower aquifer. Private wells in the residential subdivisions south of the Site have elevated levels of contaminants (EPA

2011). All residences have been connected to an alternate water source from Milan (EPA 2011).

The Site is underlain by alluvium with a saturated thickness that thins from west (50 ft or 15.2 m) to east (20 ft or 6.1 m) (Hydro-Engineering 2001). Underlying the alluvium are the Triassic-age Chinle Group and the Permian-age San Andres Limestone and Glorieta Sandstone. The underlying more permeable layers of the rocks consist of sandstone, limestone, and siltstone. The Chinle Group comprises three aquifers (upper, middle, and lower) separated by shale. Some or all of the underlying rock aquifers (the three Chinle aquifers in particular) subcrop in various locations in the San Mateo Creek Basin. The dip of the Chinle Group, San Andreas Limestone, and Glorieta Sandstone is approximately to the north, which is counter to regional flow in the alluvial aquifer, which is generally from northeast to southwest (Hydro-Engineering 2001).

Groundwater in the alluvial aquifer recharges the Chinle aquifers at subcrop locations. The rate of recharge from the alluvial aquifer to the Chinle aquifers is dependent on changes in the saturated thickness of the alluvial aquifer as waters from upgradient mining legacy locations in the San Mateo Creek Basin are transported downgradient. The lower rock aquifers are intersected by a series of faults. One set of faults trends from southwest to northeast and bounds the area of the LTP (Fig. 1b). The underlying rock aquifers are uplifted to the west of the LTP.

The Site remediation standard for U is 160 micrograms per liter ($\mu\text{g/L}$) and for Se it is 320 $\mu\text{g/L}$ for the alluvial aquifer, which is based on concentrations of contaminants of concern of well water from the alluvial groundwater interpreted as being upgradient from the Site (EPA 2011). Due to recharge of groundwater from the alluvial aquifer to the Chinle aquifers, groundwater standards are being applied to the Chinle aquifers in the affected area (called mixing zone). The remediation standards do not meet Federal drinking water standards for U (Maximum Contaminant Level (MCL) of 30 $\mu\text{g/L}$; EPA 2016) and Se (MCL of 50 $\mu\text{g/L}$; EPA 2016), which is partly due to pervasive mining activities in the upper San Mateo Creek Basin and the potential for regional contamination to impact local water quality.

Historical U concentrations in groundwater

Historical regional data for the Grants Mineral Belt area show mean background concentrations of 23 $\mu\text{g/L}$ for U in groundwater (Kaufman et al. 1976). Uranium concentrations less than 100 $\mu\text{g/L}$ for the middle to lower San Mateo Creek Basin were considered unaffected by mining activities (Gallaher and Cary 1986). In more recent work, regional U concentrations in groundwater from the San Mateo Creek Basin ranging from < 10 to 500 $\mu\text{g/L}$ have been measured (New Mexico Environment Department (NMED) 2008; 2012).

A study by EPA (2018) found U concentrations of alluvial groundwater in the San Mateo Creek Basin upgradient from the Site ranging from 2 to 300 $\mu\text{g/L}$.

Wells located far upgradient (> 0.8 km; > 0.5 mi) from the LTP (to the north) are hypothesized to be affected by regional mining/milling contamination from the upper San Mateo Creek Basin as shown by increases in contaminants associated with regional mine and milling wastes (Homestake Mining Co. 2015). Closer to the Site, proximal wells located just north of the Site (interpreted as being upgradient from the LTP; Homestake Mining Co. 2015) could be affected by local mounding and radial outflow from LTP wastewaters. Because of local mounding at the LTP, proximal wells to the north could be downgradient from the LTP despite the prevailing regional flow direction of northeast to southwest. Several of the proximal wells show a wide range of U concentrations (from 20 to 230 $\mu\text{g/L}$) based on 1995–2004 data as reported by Homestake Mining Co. (2015) and Hydro-Engineering LLC (2001).

Geochemistry of U and Se occurrence

At the concentrations of dissolved U in most natural waters, U solubility is most likely limited by sorptive processes and not by U mineral saturation (Langmuir 1978). Uranium mobility is affected by redox, pH, and aqueous complexes. The insoluble form U(IV) is predominant in U ore (Brookins 1977; Hall et al. 2017), but once exposed to the surface through mining or milling, the oxidation state becomes U(VI) (Basu et al. 2015; Van Berk and Fu 2017; Dong and Brooks 2006; Alam and Cheng 2014; Klaja and Dudek 2016), which is much more mobile in water.

Uranium roll-front type deposits have been noted in the Poison Canyon area upgradient (northwest) from the Site with the occurrence of U ore being associated, stratigraphically, near the location between coarse-grained units with oxygenated groundwater and fine-grained interbeds with reduced groundwater (Turner-Peterson and Fishman 1986). Roll-front deposits that form in oxidized to reduced zones have a preferential sequence of deposition from (1) Se with hematite, (2) vanadiferous clay plus U silicate or oxide plus pyrite or marcasite, and (3) pyrite or marcasite plus jordanite (Brookins 1977). Oxidizing agents can remove pyrite and carboniferous material. Some studies have shown an association of U with carbon-rich environments, whereas others have shown no association (Fabricius et al. 2003).

Selenium has been associated with salts and irrigation water in arid environments such as New Mexico. Selenium occurs in four oxidation states as selenate (SeO_4^{2-} , 6+ oxidation state), selenite (SeO_3^{2-} , 4+ oxidation state), elemental selenium (Se^0 , neutral), and selenide (Se^{2-} , 2– oxidation state) (McNeal and Balistrieri 1989). Selenate and selenide generally are soluble in water, whereas elemental Se and

most forms of selenide are insoluble (Bailey et al. 2012; Masscheleyn et al. 1990; Gates et al. 2009; Mast et al. 2014). Selenate is highly mobile, especially under alkaline and oxidizing conditions (Naftz and Rice 1989), because its salts are highly soluble and it is weakly adsorbed to particles (McNeal and Balistrieri 1989). Selenite is stable in alkaline to mildly acidic conditions and is more readily immobilized by adsorption onto clay minerals, organic matter, and iron oxyhydroxides (McNeal and Balistrieri 1989; Balistrieri and Chao 1990; Boulton et al. 1998). Microbial action can change the speciation of Se through changes in redox state or the formation of organic Se compounds (Wright 1999; Gates et al. 2009; Bailey et al. 2012; McNeal and Balistrieri 1989; Kulp and Pratt 2004; Dubrovsky et al. 1990).

Approach

Uranium variability at 6 monitoring wells (Fig. 1b) was assessed relative to the level of heterogeneity of the formation to gain insight into U occurrence from natural and anthropogenic sources. The 6 monitoring wells are located upgradient (to the north), proximal, and downgradient (to the south) from a local U source (Site). Well construction information for the 6 monitoring wells is included in supplemental information (s1). We examined the level of heterogeneity in alluvial stratigraphy with a standard suite of borehole geophysical logs including natural gamma-ray (NGR). Because NGR is a bulk signal and responds to K, Th, and U combined, we also utilized spectral gamma-ray (SGR) logging to help differentiate NGR responses (Keys 1990). In addition to NGR and SGR, the other borehole geophysical logging (electromagnetic (EM) induction, fluid conductivity and temperature logs, flowmeter) was used to identify the level of the physical and potential chemical heterogeneity of the alluvium, confirm well construction and condition (optical televiewer log), determine which hydrogeologic layers each well screen is open to, the degree of mixing external to the well in the formation (EM induction logs) and internal to the well (fluid conductivity and temperature logs), and to identify the lithology, mineralogy, and gamma emitting elements (NGR and SGR logs).

The synthesis of results from borehole logging can help discern the degree of heterogeneity and fluid mixing in wells. For example, the variability in the NGR log can identify interbedding and contrasting lithologic and mineralogic layering in the alluvium. Large differences between maximum and minimum measurements indicate large contrasts in bedding. The relation between K, U, and Th can be used for distinguishing the type of minerals, type of deposits, and the presence of organic matter. Organic matter content in rocks can be a factor in binding U in reducing environments. Thorium is an indicator of clay content, types of clay minerals, and heavy minerals in igneous rock (not applicable in

the study area). Potassium (K) is an important component in shales and is an indicator of feldspars and micas; K generally occurs in oxidized form. The ratio of Th/K is important for distinguishing the type of clay minerals (Klaja and Dudek 2016).

Coupled with the logging, vertical strings of passive samplers were deployed along potential stratigraphic and other hydrochemical boundaries as identified from the borehole logging. The passive samplers were used to profile the well for aqueous U and Se concentrations under ambient conditions. In this way, the bulk signal (aquifer and water) from the borehole geophysical logs can be compared to the aqueous concentrations measured from water in the passive sampler.

We also determined U and Se concentrations in purge samples that represent water from different parts of the formation than the water from the passive samplers. The two purge sample methods included micropurge (small volume) and volumetric (large volume). A schematic identifying the potential differences in sample zones based on sample method is shown in Fig. 2. The micropurge sample method collected water from a small zone of the well and likely from a small zone of the formation (Fig. 2). In contrast, samples collected during volumetric pumping of a well,

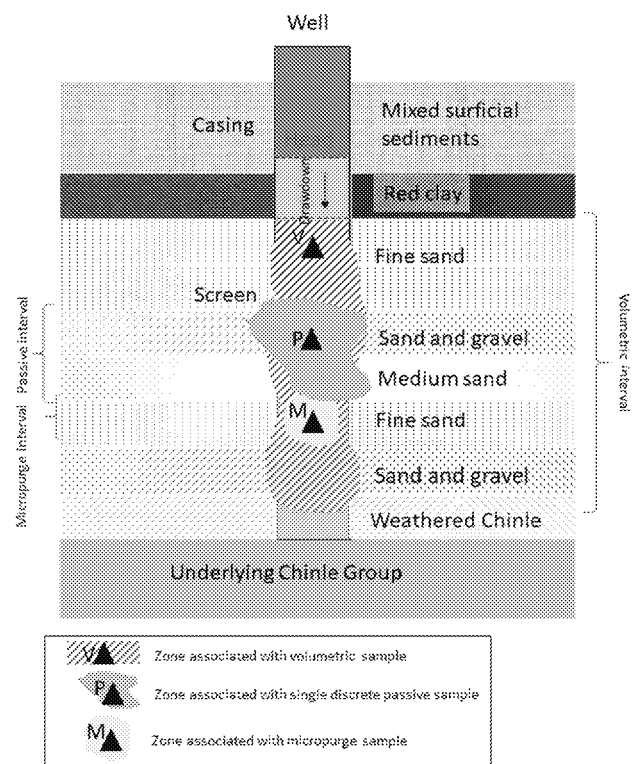


Fig. 2 A schematic of sample zones for the different sampling methods (This figure shows a conceptual view of a sampler zone associated with one single passive sampler. For a vertical profile of passive samplers, a larger vertical sample zone would result)

where large volumes of water are pumped, are intrinsically flow-weighted and preferentially collected water from the more permeable units. Volumetric samples likely collected water from a larger interval of the well and formation than the other methods (Fig. 2). For passive samples, the zone of sample is likely smaller than the volumetric sample but may be comparable to the micropurge sample (Fig. 2). The sample zone for the passive sampler is particularly dependent on the ambient flow patterns of the well (i.e., intraborehole flow).

Methods

Borehole geophysics

Conventional borehole geophysical logs were collected at the 6 monitoring wells (supplemental information s1) and included optical televiewer, caliper, NGR and SGR, fluid conductivity, fluid temperature, and EM induction logs. Three wells had vertical-differential flowmeter logs run under ambient and stressed (pumped) conditions. The geophysical data are available at <https://doi.org/10.5066/F7CR5RJS> (Harte et al. 2018b).

All borehole geophysical data were collected using a Century Geophysical Corporation system VI logging system or a Mount Sopris Instruments Matrix logging system. For this study, the Mount Sopris Instruments system was used to collect optical televiewer, fluid property, and SGR logs; all other logs were collected using the Century Geophysical Corporation system. Limitations, calibration procedures, and algorithms of the geophysical probes are available from the manufacturers (Century Geophysical Corporation 2017; Mount Sopris Instruments 2017).

All logs were collected according to the American Society of Testing and Materials (ASTM) borehole geophysical standard procedures (ASTM 2004, 2007, 2010). Geophysical logs were collected in digital format and were recorded in the proprietary format of the data acquisition equipment used to collect the logs. These proprietary data formats were converted to and stored as Log American Standard (LAS) Code for Information Interchange (ASCII) Standard (Canadian Well Logging Society 2013) for tabular data and presented as chart logs in a portable document format (PDF) file (Harte et al. 2018b). Only the NGR and SGR logs are described in detail here. Information on other logs (fluid, EM induction, and EM flowmeter) can be found in Keys (1990).

The NGR logs provide a record of gamma radiation measured in a borehole and are unaffected by well fluids. A scintillation detector is used in NGR tools to measure the natural gamma-ray emission from radioactive material in the formation. The primary emitters are potassium (^{40}K), ^{238}U ,

and thorium (^{232}Th). As each of these isotopes decay, the energy released contributes to the total NGR log. Typically, fine-grained sediments that contain abundant clay tend to be more radioactive than coarse-grained sediments, quartz sandstones, or carbonates (Keys 1990). The unit of measurement is API (American Petroleum Institute units).

The SGR logs were used to identify individual gamma emitters from the potassium (^{40}K), uranium (^{238}U) and thorium (^{232}Th) decay series encountered in the alluvium and underlying formations (Ehrenberg and Svåná 2001). The K isotope is directly detected by its gamma emission, whereas the U and Th emitters show up through the signatures of daughter products, and the SGR assumes radiometric equilibrium has been achieved before counts in the U and Th spectral windows can be quantitatively related to the presence of these elements. A Mount Sopris 2lsa-1000 large-crystal-spectral-gamma probe (<https://mountsopris.com/items/2lsa-1000-large-crystal-spectral-gamma/>) was used.

The SGR logs were collected in nonstationary (trolling) and stationary (parked) modes. Nonstationary mode (trolling) was carried out similar to other logs by moving the tool up or down at a fixed rate (3–10 ft/min or 0.9–3.3 m/min). There is some uncertainty about the reliability of SGR logs in trolling mode and for this reason we chose to look at bulk responses of the individual gamma emitters. We used the relative ranking of a well's summary statistics from trolling measurements to assess trends. Stationary mode was collected at 3–8 specific depths per well and measurements allowed to stack to collect a more statistically robust measurement that was then averaged and reported. The stacked measurements (from below the water table) are generally in agreement within one or two ranked positions with the trolling statistics for most wells meaning if the well fluid had a relatively high or low radioactive element concentration for the trolling statistics this was also the case for stacked measurements based on mean statistics.

Chemical profiling and groundwater sampling

Passive, micropurge, and volumetric groundwater samples were collected in July–October 2016 for this study (Fig. 2). All collected samples were kept on ice and submitted for laboratory analysis for U and Se, as described in the following section “Laboratory Analysis.” Additional groundwater sampling details are provided in Harte et al. (2018a).

Passive samples were collected first in the sampling process. Nylon screen (NS) passive samplers were used to collect the passive samples and map the vertical variation in well chemistry (specifically U and Se). A maximum number of 11 NS passive samplers was deployed at well T11, and all wells had at least 7 samplers. The NS passive samplers (Vroblesky et al. 2002, 2003a, b) were deployed in 6 monitoring wells according to methods described by Harte et al.

(2018a). The NS mesh has a 125-micrometer opening and represents a quasi-filtered sample. However, because the NS mesh is coarser than a 0.45-micrometer filter commonly used to collect dissolved samples, the sample is designated as total (unfiltered).

The micropurge sample was collected second. The primary purpose of a micropurge sample was to allow a direct comparison to the results of the passive samplers, which serves as calibration of the passive sampler.

Volumetric samples were collected last. Volumetric samples were collected after removal of a quantified volume (three times the volume of water in the static water column of the well casing and screen prior to sample collection), to achieve a representative sample of groundwater (Harte et al. 2018a). During volumetric purging, concurrent monitoring measurements of field parameters were collected until the readings stabilized, which helped ensure the capture of formation water (USGS, variously dated; Harte et al. 2018a, b). The pump intake was set in the solid casing, just above the top of the screen. In the absence of water in the casing (called casing water), the pump intake was placed at the midpoint of the open interval.

Laboratory analysis

Groundwater samples for U and Se concentrations were analyzed by EPA method 6020A (inductively coupled plasma mass spectrometry (ICPMS)) at RTI labs, Livonia, MI. A subset of dissolved U samples was submitted to the EPA Region 6 lab for further analysis (ICPMS, EPA 200 series, method ILMO5.3; Martin 2003). A detailed report of laboratory concentrations and quality control and assurance is provided in Harte et al. (2018a).

Geophysical logging results

Both the NGR and EM induction logs for the six wells show variability with depth indicating various levels of heterogeneity as inferred from geophysical logs. Two wells (ND and DD) are highlighted to illustrate the type of heterogeneity encountered (Figs. 3, 4). Groundwater from wells ND and DD have relatively low and high historical U concentrations, respectively (Hydro-Engineering 2001).

At well ND, a brown sand layer [Fig. 3; depth of 35 ft or 10.7 m below land surface (bls)] is associated with an

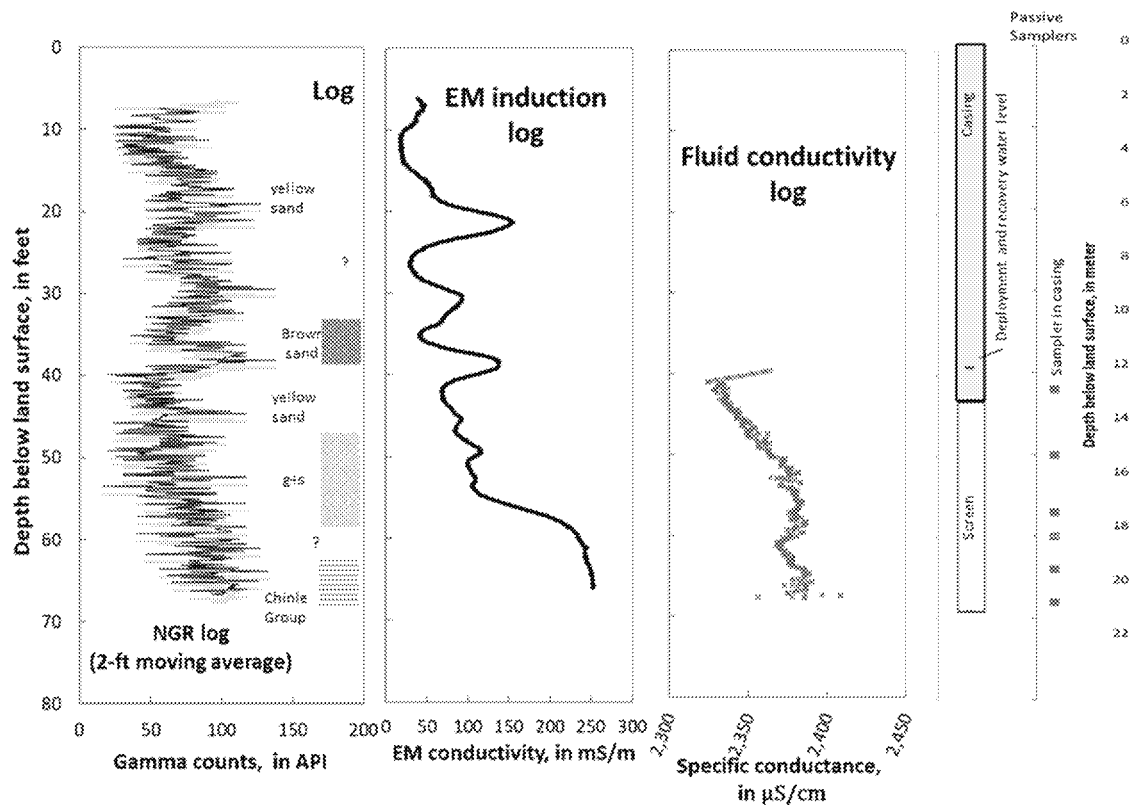


Fig. 3 Borehole geophysical logs (NGR, EM induction, and ambient fluid conductivity) and passive sampler deployment depths for well ND, Homestake Superfund site, near Milan, New Mexico [Dark

line for NGR is 2-ft (0.61-m) moving average plotted with raw data (Harte et al. 2018b); *ms* medium sand, *fs* fine sand, *cg* coarse gravel, *g* gravel, ? unknown]

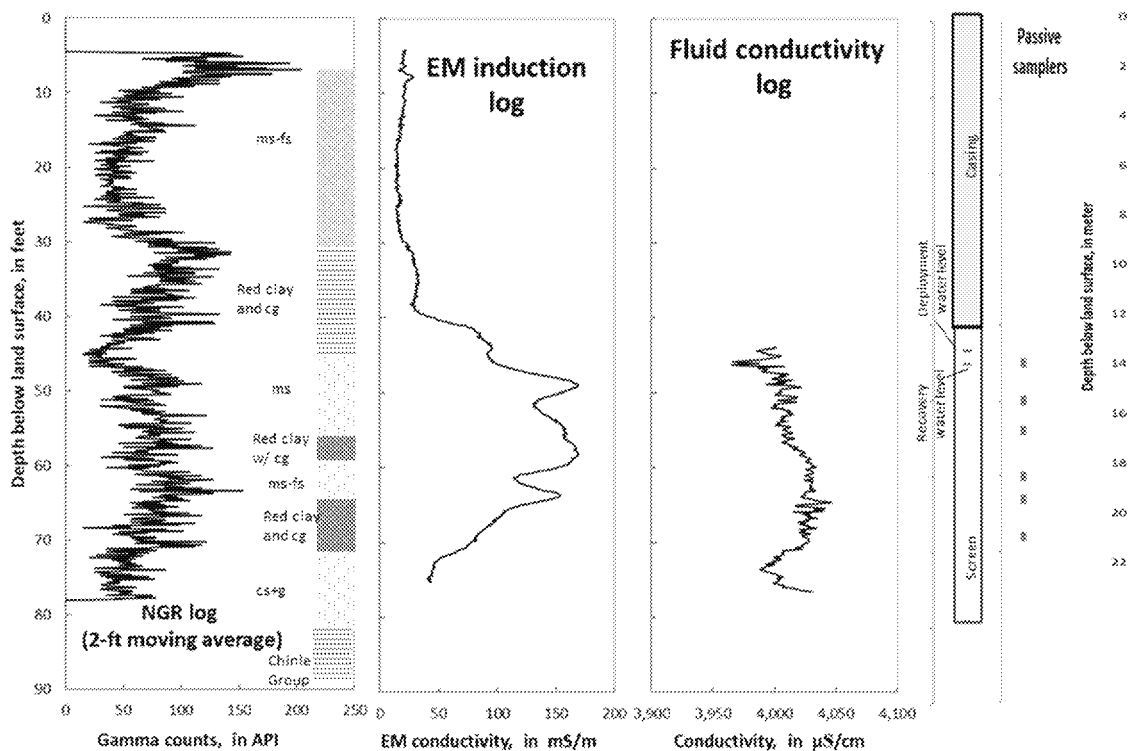


Fig. 4 Borehole geophysical logs (NGR, EM induction, and ambient fluid conductivity) and passive sampler deployment depths for well DD, Homestake Superfund site, near Milan, New Mexico. [Dark

line for NGR is 2-ft (0.61-m) moving average plotted with raw data (Harte et al. 2018b); *ms* medium sand, *fs* fine sand, *cg* coarse gravel, *g* gravel]

increase in the NGR log. An increase in the NGR log also occurs at the bottom of the well in the Chinle Group. The EM induction log shows a spike in conductivity coinciding with the yellow sand (Fig. 3; depth of 42 ft or 12.8 m bls). Because that depth (42 ft or 12.8 m bls) is near the water table, trapped pore fluid likely is present near the water table. The EM induction log also shows an increase in conductivity corresponding to the Chinle Group at the bottom of the well similar to the NGR increase, indicating a formation change. The ambient fluid conductivity log, while showing generally little change in conductivity with depth in the well, shows a slight increase at the yellow sand layer (depth of 42 ft or 12.8 m bls) similar to the EM induction log, indicating a fluid change and some stratified inflow into the well.

At well DD, several of the red clay layers are associated with higher NGR counts (Fig. 4; depths of 37 ft or 11.3 m, 58 ft or 17.7 m, and 64 ft or 19.5 m bls). Parts of the medium sand (*ms*) (Fig. 4; *ms* at 50 ft or 15.2 m and 62 ft or 18.9 m bls) and the coarse sand (*cs*) and gravel (*g*) (Fig. 4; *cs + g* at 72 ft or 21.9 m bls) are associated with lower NGR counts. The EM induction log shows a spike near the water table in the *ms* layer (Fig. 4; 49 ft or 14.9 m bls) but otherwise shows relatively low EM conductivity elsewhere in the *ms* and *cs + g* layers. The fluid conductivity log shows negligible change at that same depth of 49 ft or 14.9 m bls, indicating

that the EM conductivity increase is associated with a sediment change as shown by the NGR log. In contrast, both the EM induction log and fluid conductivity log show a decrease in the *cs + g* layer at a depth of 73 ft or 22.3 m bls, indicating fluid chemistry changes and stratified inflow, respectively (Fig. 4).

A summary of bulk geophysical characteristics per well is provided in Table 1. Well Q had the greatest difference in NGR counts (API units), whereas wells ND and DD2 the least (Table 1). In contrast, well Q had the least variability in EM conductivity whereas well T11 had the most. Wells ND and DD2 had a similar range of variability in EM conductivity. Little variation of the fluid conductivity log, like at well Q, indicates either a well-mixed aquifer or a well that is dominated by ambient flow from one layer. Larger variation in the fluid conductivity log, like at well T11, indicates chemical constituents with different electrical properties flowing into the well at different depths from a stratified inflow. Therefore, low variability in the ambient fluid conductivity log does not preclude different water chemistry external to the well with depth, as high variability often is indicative of a formation with different water chemistry with depth.

Upward ambient fluid flow was measured at well DD from the bottom of the well near the basal alluvium and

Table 1 Summary of geophysical log parameters used to assess the degree of heterogeneity of the formation and relative amount of in-well mixing, Homestake Superfund site, near Milan, New Mexico

Parameter	Units	Well name					
		Q	ND	DD	DD2	T11	MV
Difference in minimum and maximum natural gamma-ray (NGR) measurement (saturated section)	(API)	204	117	138	112	158	150
Difference in minimum and maximum electromagnetic (EM) conductivity measurement (saturated section)	(mmho/m)	4	184	129	192	219	148
Ambient fluid logs (conductivity and temperature) show variability with depth	(Y is $\geq \pm 20\%$ between minimum and maximum; otherwise N)	Y; only varied within casing but not the screen	Y	Y; only at the bottom of well	N	Y; increasing conductivity with depth	Y
Flow detected with flowmeter under ambient conditions	(Y or N)	N	N	Y; (most inflow at 73 to 64 ft bls or 22.3 to 19.5 m bls; outflow from 64 to 54 ft bls or 19.5 to 16.5 m bls)	–	–	–
Location of flow distribution measured with flowmeter under pumped conditions	Depth (ft)	Most inflow from top of screen (68 ft bls or 20.7 m bls) to 78 ft bls or 23.8 m bls	Most inflow from bottom of screen below 60 ft bls or 18.3 m bls (well screen to 64 ft bls or 19.5 m bls)	Most inflow from 62 to 72 ft bls or 18.9 to 22 m bls near the bottom of the well (well screen to 78 ft bls or 23.8 m bls)	–	–	–

– no data, *API* American Petroleum Institute units, *mmho/m* millimhos per meter, *Y* yes, *N* no, *bls* below land surface, *ft* feet, *m* meter

underlying Chinle Group by the flowmeter (Table 1). The fluid conductivity also indicates that a horizontally stratified flow takes place under ambient conditions at well DD. Flow during pumping conditions showed a preferential inflow at all three wells measured by the flowmeter (Q, ND, and DD). Well Q had an inflow near the top of the screen, whereas wells ND and DD had inflows near the bottom of the screen.

Summary statistics on the NGR log results and the SGR log results (mean K, U, and Th) are in Table 2 and provide information on gross responses per well from the radioactive signature of the lithology and mineralogy of the formation. Well MV had the lowest mean NGR counts, indicating less fine-grained sediments are present; whereas well ND had the highest mean NGR counts, indicating more fine-grained sediments are present. The standard deviation of the NGR counts was lowest in well DD2, indicating less variability, and highest in well Q. However, the lithologic logs indicate a thick clay layer and thin sand layers at wells DD and DD2 (Homestake Mining Co., written commun. 2016). Bed thickness affects the NGR response and the thin sand layers may suppress NGR responses and limit NGR variation. In well Q, the variation is due to one particular spike of NGR counts at 85 ft or 25.1 m bls [supplemental information well characteristic Table (s2)]. Well T11 had the lowest mean K of 11.6 picocuries per gram (pCi/gm) and well ND the highest mean K of 23.5 pCi/gm. The variation in U was much

smaller among the wells indicating that U is ubiquitous in the alluvium and upper Chinle Group. Counts of Th were lower than counts of K and U in all wells (Table 2).

The relation between the principal radioactive elements is an indicator of the lithologic and mineralogic composition of the formation and the chemical sorption processes taking place. Individually, the NGR log and the U, K, and Th from the SGR logs are poorly correlated (Table 3) using the Pearson Product-Moment Correlation Coefficient at 95% confidence level (Helsel and Hirsch 2002). This indicates that the presence of U, K, and Th is depth specific and no bulk trend is readily observable. The exception is well T11 where NGR and U from the SGR log are well correlated, and to a lesser extent well MV; wells DD, ND, and DD2 group together. Well T11 is drilled into the LTP. K and Th from the SGR logs are generally positively correlated, and this is indicative of the presence of clay minerals such as illite (Klaja and Dudek 2016). U and Th from the SGR logs are negatively correlated as are K and U (Table 3).

In wells ND, DD, and DD2, a reddish to brown sand and clay layer was found at a depth of approximately 40 ft or 12.2 m below land surface (bls) (supplemental information s2). The water table was found immediately below this depth. The NGR and SGR logs had an increase in API and U in pCi/gm, respectively, that was associated with the layer at 40 ft or 12.2 m bls. Wells DD and DD2 had interbedded

Table 2 Summary of natural gamma-ray (NGR) and spectral gamma-ray (SGR) logging results, Homestake Superfund site, near Milan, New Mexico

Log parameter	Units	Well name					
		Q	ND	DD	DD2	T11	MV
Mean gamma (NGR)	(API)	71.4	74.7	67.3	69.6	88.1	61.3
Stdevp gamma (NGR)	(API)	34.5	25.2	24.4	20.2	32.8	33.4
Mean K-spectral (SGR)	(pCi/gm)	17.1	23.5	16.5	14.6	11.6	15
Mean U-spectral (SGR)	(pCi/gm)	3.6	3.6	3.6	3.3	3.9	2.8
Mean Th-spectral (SGR)	(pCi/gm)	2.0	2.4	1.7	1.6	1.4	1.3

API American Petroleum Institute units, *pCi/gm* picocuries per gram, *Stdevp* standard deviation of the population; data from screen opening of well

Table 3 Natural gamma-ray (NGR) and spectral gamma-ray (SGR) correlation coefficient between paired radioactive elements, Homestake Superfund site, near Milan, New Mexico

Correlation pairs	Units	Well name					
		Q	ND	DD	DD2	T11	MV
NGR to SGR-U	(API)–(pCi/gm)	0.11*	0.03*	0.00*	0.02*	0.70	0.25
NGR to SGR-K	(API)–(pCi/gm)	0.02*	0.03*	−0.27	0.10*	0.60	0.01*
NGR to SGR-Th	(API)–(pCi/gm)	0.04*	0.10*	0.14	0.02*	−0.54	0.06*
SGR-K to SGR-U	(pCi/gm)	−0.81	−0.88	−0.88	−0.79	0.68	−0.83
SGR-U to SGR-Th	(pCi/gm)	−0.86	−0.90	−0.86	−0.88	−0.77	−0.87
SGR-K to SGR-Th	(pCi/gm)	0.71	0.74	0.79	0.68	−0.43	0.78

Statistics for entire logged section of well; *U* uranium, *K* potassium, *Th* thorium, *NGR* natural gamma-ray, *SGR* spectral gamma-ray, *Correlation* Pearson Product-Moment Correlation Coefficient, *API* American Petroleum Institute units, *pCi/gm* picocuries per gram

*Not significant at the 95% confidence level

clays and sand layers along the screen interval that may promote the contact between more oxic waters from sand layers and reduced waters from clay beds, whereas wells Q and ND had less clay. It is inferred from the NGR log that well MV has a coarse-grained upper layer overlying a fine-grained lower layer. At well T11, the tailings pile is clearly identifiable by high NGR and U as identified in the SGR log along the upper part of the well above the water level depth of 100 ft or 32.8 m bls.

Sampling results

Comparison of sampling

Harte et al. (2018a) showed that the aqueous U and Se concentration results from the NS passive samplers were consistently underestimated in comparison to the purge (micropurge or volumetric) sample concentrations; however, the relation between the two methods was linear. This relation allowed for a correction to be applied to the concentration results for the passive samplers (Harte et al. 2018a). The ratio of concentrations between the passive and purge samples was 0.2811 for U and 0.2888 for Se. All passive sampler concentrations reported in this paper were adjusted by a factor of 3.55 ($1/0.2811$) for U and a factor of 3.46 ($1/0.2888$) for Se to adjust results to an equivalent micropurge concentration, according to the methods described by Harte et al. (2018a). These adjustment factors are consistent with the diffusion rates of U and Se, deployment times, and dimensions of the samplers as identified in supplemental information presented with this paper (s3, s4).

U concentration results from the three different sampling methods at the six monitoring wells are summarized in Table 4. The U concentrations from the volumetric and micropurge samples are in close agreement. The 6 volumetric samples from the 6 wells and the 7 micropurge samples (2 micropurge samples were collected at well DD2) from the 6 wells yielded similar concentrations indicating that well water within the screen under ambient conditions is representative of the formation. The micropurge samples are instantaneous samples collected without inducing well inflow from pumping and therefore represent the in-situ water in the screen at that interval. Volumetric sampling, which requires large amounts of purging, is, therefore, not needed to collect a representative sample. The largest difference (56 $\mu\text{g/L}$) between the volumetric (297 $\mu\text{g/L}$) and micropurge (353 $\mu\text{g/L}$) samples is from well MV. The volumetric sample at well MV was collected at 71 ft or 21.6 m bls (near bottom of casing and top of well screen) and the micropurge sample was collected at 82 ft or 25 m bls, within the screen interval. The vertical profile of U from well MV shows a net increase

of 60 $\mu\text{g/L}$ with depth from 67 to 82 ft or 20.4 to 25 m bls (Harte et al. 2018a). We conclude that the volumetric sample for well MV captures some water from the well casing based on relative concentration differences from the vertical profile of U.

The variability in concentrations from the passive sampling profile can be identified by the relative magnitude of the standard deviation of U concentrations from the passive samplers (Table 4). The concentration of U for passive sampling shows small variation at 2 of the wells profiled (wells ND and Q; Table 4) and larger variations at 4 of the wells (wells MV, DD, DD2, T11; Table 4). Well T11 had the highest mean U concentration and largest standard deviation from the profile of passive samplers and is located at the LTP (Fig. 1b). Based on the trend of the profile (Fig. 7), we attribute the variability to differences in lateral transport of U from different parts of the LTP. Well ND had the lowest mean U concentration but not the lowest standard deviation from the profile of passive samplers and is located northeast of the LTP (Fig. 1b). Well Q had the smallest standard deviation that indicates that the well and potentially the formation is well mixed with little vertical variation in U concentrations in groundwater. Wells DD, DD2, and MV are located proximal to the LTP (Fig. 1b). Despite the proximity to well DD, well DD2 water had a larger variation in U concentrations than well DD water. Wells ND and Q are screened in predominantly silt and sands, whereas wells DD and DD2 are screened in interbedded clays and silts and sands. Well MV is screened in sands and is located downgradient from the LTP and likely receives U groundwater transport from the LTP.

Physical heterogeneity of the alluvium likely affects the U concentration variability. The interbedded clays at wells DD and DD2 may contain reduced waters where U in the form of U(IV) may be sorbed onto sediments and in proximity to oxic waters that induce mobilization of U by converting U(IV) to mobile U(VI). Where there are primarily sands and silts (wells ND and Q), the aquifer is well mixed and has less U variability.

Concentrations of U in groundwater, excluding that in well T11, varied by one order of magnitude, ranging from 25 (well ND) to 297 $\mu\text{g/L}$ (well MV) in volumetric samples, 31 (well ND) to 353 $\mu\text{g/L}$ (well MV) in micropurge samples, and the mean passive sample from the chemical profiles varied from 24 (well ND) to 313 $\mu\text{g/L}$ (well MV) (Table 4). Individual passive sampler concentrations ranged from 12 (well ND) to 351 $\mu\text{g/L}$ (well MV) (Harte et al. 2018a). In wells where casing water was present and passive samplers were set in the casing water (wells MV, Q, and DD2), the U concentrations were lower than the concentration of the passive samplers set in the screens (Table 4).

Table 4 Summary of aqueous uranium (U) concentrations [micrograms per liter ($\mu\text{g/L}$)] from multiple types of sampling methods including passive sampling, Homestake Superfund site, near Milan, New Mexico

Type of sample	Parameter	Sample description	Units	Well name						
				ND	MV	Q	DD	DD2	DD2	T11
Volumetric	Total uranium	Sample collected after evacuation of three well volumes	($\mu\text{g/L}$)	25	297	66	103	250	—	10,677
Micropurge	Sample depth below LSD		(ft)/(m)	49/14.9	71/21.6	68/20.7	54/16.5	50/15.2	—	140/42.7
	Total uranium	Sample collected after evacuation of pump and hose volume	($\mu\text{g/L}$)	31	353	61	90	263	257	10,353
^a Passive	Sample depth below LSD		(ft)/(m)	64/19.5	82/25	88/26.8	54/16.5	72/22	60/18.3	140/42.7
	Number of samples			7	9	9	7	12	—	11
	Mean total uranium	Mean concentration from profile of passive samples including casing sample	($\mu\text{g/L}$)	24	313	53	^b 65	167	—	16,508
	Total uranium	Passive sample located within casing (casing sample)	($\mu\text{g/L}$)	None	238	46	None	44	—	None
	Mean total uranium	Mean concentration from profile of passive samples excluding sample from casing zone	($\mu\text{g/L}$)	24	322	54	^b 65	180	—	16,508
	Standard deviation of total uranium	Excludes passive sample from casing zone	($\mu\text{g/L}$)	6.4	23.4	3.7	^b 23.8	50.5	—	7502

Bold highest value between volumetric and micropurge sample, *none* no sample, — use previous value from same well, *LSD* land surface datum, *ft* feet, *m* meter, Uranium concentrations from Harte et al. (2018a)

^aPassive sampler concentrations were adjusted by a factor 3.55 (1/0.2811) for U according to Harte et al. (2018a)

^bUppermost sampler possibly exposed due to shallow water levels

Table 5 Summary of aqueous Se concentrations [micrograms per liter ($\mu\text{g/L}$)] from multiple types of sample methods including passive sampling, Homestake Superfund site, near Milan, New Mexico

Type of sample	Parameter	Sample description	Units	Well name						
				ND	MV	Q	DD	DD2	DD2	T11
Volumetric	Total selenium	Sample collected after evacuation of three-well volumes	($\mu\text{g/L}$)	150	35	460	130	13	–	180
	Depth of sample below LSD		(ft)/(m)	49/14.9	71/21.6	68/20.7	54/16.5	50/15.2	–	140/42.7
Micropurge	Total selenium	Sample collected after evacuation of pump and hose volume	($\mu\text{g/L}$)	51	29	380	170	2	8	350
	Depth of sample below LSD		(ft)/(m)	64/19.5	82/25	88/26.8	54/16.5	72/22	60/18.3	140/42.7
^a Passive	Number of samples			7	9	9	7	11	11	12
	Mean total selenium	Mean concentration from profile of passive samples including casing sample	($\mu\text{g/L}$)	65	26	408	^b 152	6	–	121
	Total selenium	Passive sample located within casing (casing sample)	($\mu\text{g/L}$)	None	15	381	None	< 1.5	–	None
	Mean total selenium	Mean concentration from profile of passive samples excluding casing sample	($\mu\text{g/L}$)	65	28	411	^b 152	13	–	121
	Standard deviation of selenium	Exclude sample from casing	($\mu\text{g/L}$)	23.7	8.2	20.8	^b 23.7	3.3	–	75.1

Bold highest value between volumetric and micropurge sample, *none* no sample, – use previous value from same well; LSD means land surface datum, *ft* feet, *m* meter

^aPassive sampler concentrations were adjusted by a factor of 3.46 (1/0.2888) for Se according to Harte et al. (2018a)

^bUppermost sampler possibly exposed due to shallow water levels

Aqueous Se concentration results from the three different sampling methods in the six monitoring wells are summarized in Table 5. The 6 volumetric samples from the 6 wells and the 7 micropurge samples from the 6 wells yielded similar concentrations in 4 of the 6 wells.

The relatively variability of Se, like the relative variability of U, is high at wells T11 and MV; these wells are likely influenced by local anthropogenic sources of contamination. In two wells (ND and Q) that show little variation in U concentration (Table 4), the Se concentration shows a greater variability (Table 5). Well DD2 has some variability in U concentrations but little variability in Se concentrations (Table 5). Se like U is affected by redox conditions and Se (and U) is less mobile under reducing conditions. Well DD2 had low dissolved oxygen (D.O.) concentrations [< 1 milligram per liter (mg/L)] and low Se concentrations (Harte et al. 2018b). In contrast, well DD located near well DD2 had higher D.O. concentration (3.9 mg/L), and Se concentrations

were higher at well DD than well DD2 (Table 5). Well Q, despite showing little variability in U concentrations, had a greater variability in Se concentrations. In wells where casing water was present and passive samplers were set in the casing water (wells MV, Q, and DD2), the concentrations were typically lower than the concentration of the passive samplers set in the screens (Table 5). The exception was in well MV where the Se concentration (6 $\mu\text{g/L}$) was lowest at the lowermost sampler (102 ft or 31.1 m bsl; Harte et al. 2018a) and may represent concentrations more indicative of groundwater from the Chinle Group than the other samplers in that well.

U and Se from passive samplers

The co-occurrence of aqueous U and Se concentrations is used here as a marker of anthropogenic sources of contamination. We used the co-occurrence of aqueous U and

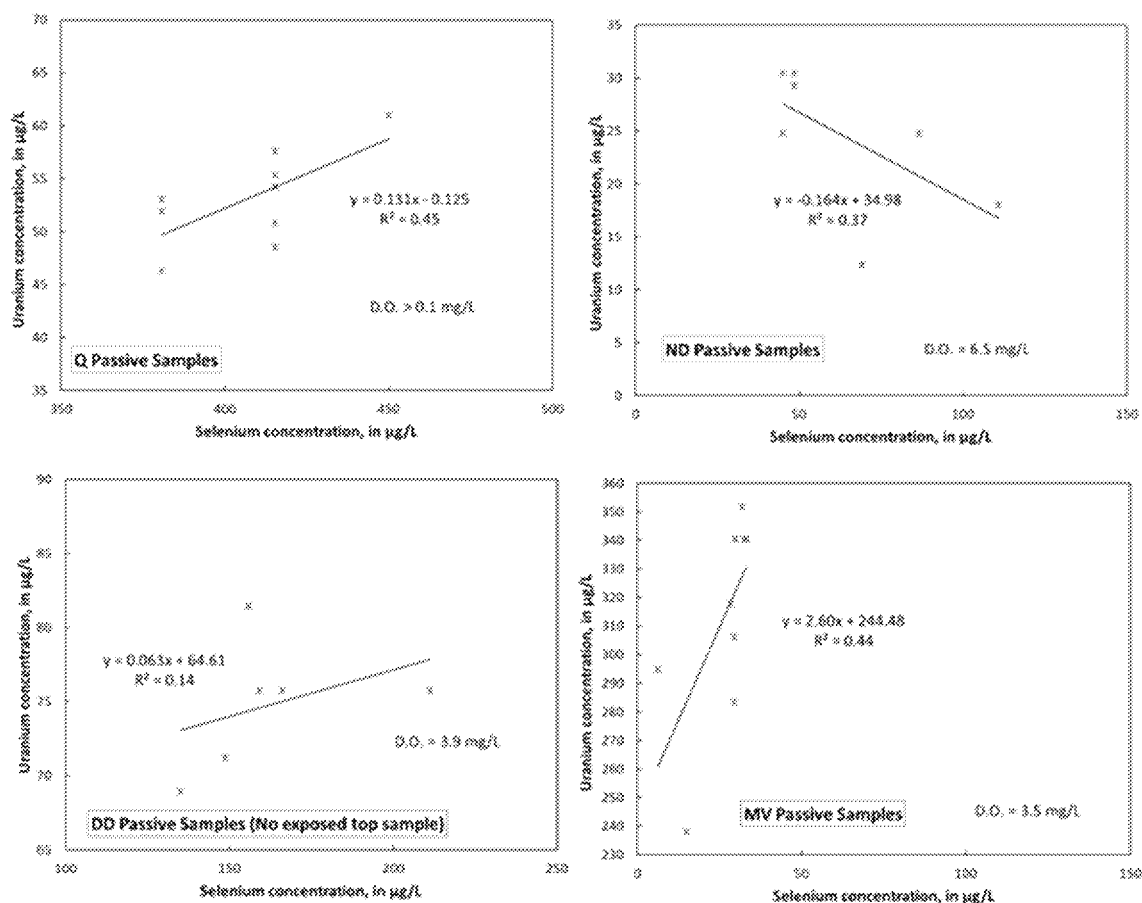


Fig. 5 Cross plots of aqueous U and Se concentrations in micrograms per liter ($\mu\text{g/L}$) from passive samplers, Homestake Superfund site, near Milan, New Mexico [U and Se concentrations were adjusted

according to Harte et al. (2018a); dissolved oxygen (D.O.) concentration given in milligrams per liter (mg/L)]

Se concentrations from the passive samplers to provide a larger population to evaluate well specific trends. Results are shown for wells DD, ND, Q, and MV to highlight contrasting results (Fig. 5). A particularly poor regression of co-occurrence concentrations provides insight into whether the anthropogenic signal is weak. Linear regression of U and Se concentrations for wells DD [coefficient of determination (R^2)=0.14; probability value (p)=0.46; Fig. 5] and DD2 (R^2 =0.28; p =0.09; not shown) shows weak relations that are not statistically significant at the 95% confidence interval. Well T11 (not shown) also had a poor R^2 (0.06) due to the large range of U concentrations at the LTP. In contrast, linear regression of U and Se concentrations had the highest R^2 for well Q (R^2 =0.45; p =0.05) and well MV (R^2 =0.44; p =0.05). These wells are interpreted as being affected by regional milling operations for well Q and local operations (Site) for well MV given their locations. Therefore, both sources of U contamination have signatures of Se contamination. Well ND shows an inverse relation with an R^2 of 0.37 (p =0.14). We interpret this as the effect of upwelling of

Chinle Group waters that have relatively higher U and lower Se concentrations than the alluvial aquifer at this location.

One-half of the six wells have a discernible trend in Se and U vertical concentration profiles as measured by the passive samplers (Figs. 6, 7). The trend is most discernible in well T11 and, although drilled through the LTP, the increasing trend in depth with Se and U indicates that lateral transport of these contaminants is affecting concentrations in this well rather than vertical transport alone. The borehole geophysical logs for T11 indicate a permeable layer in the Chinle Group at an approximate depth of 180 ft or 54.9 m bbls that appears to be transporting contaminants (Harte et al. 2018a).

Comparison of passive sampling and borehole geophysical logs

The bulk gamma response from the NGR log compares poorly to U and Se concentrations (Table 6). This may in part be related to anthropogenic sources and transport of

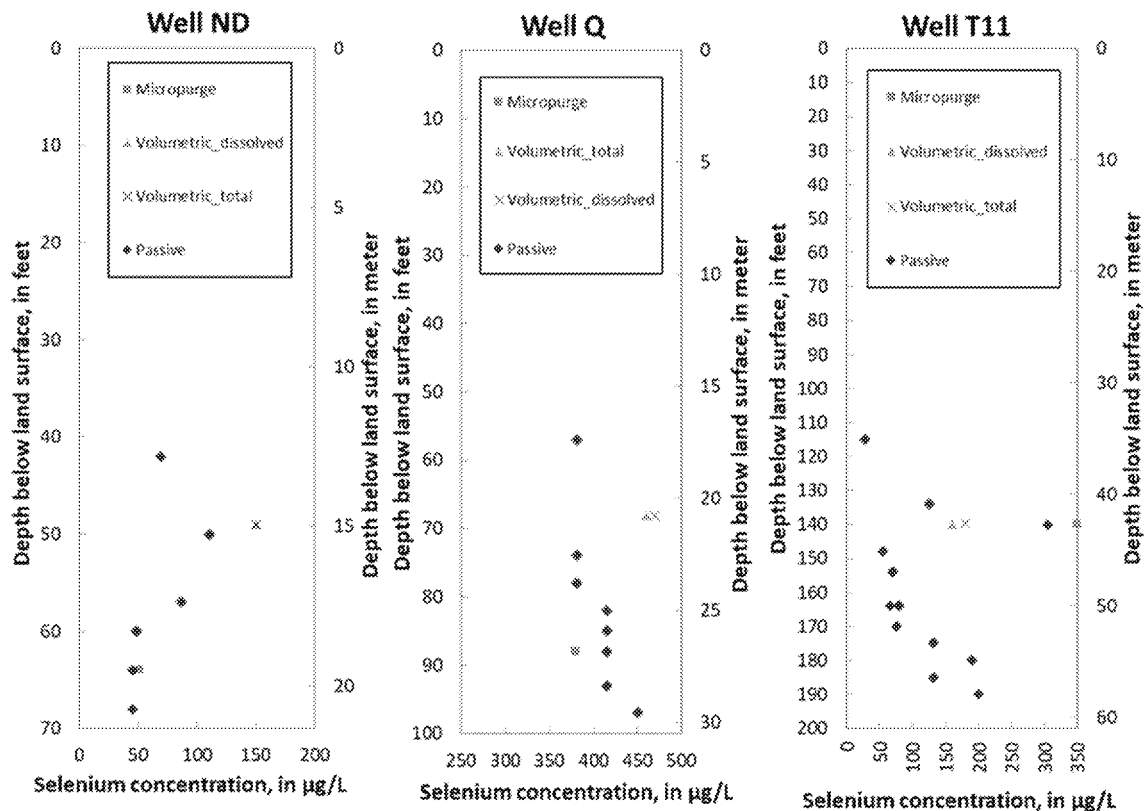


Fig. 6 Vertical profiles of aqueous Se concentrations from passive samplers and concentrations from purge (micropurge and volumetric) samples, Homestake Superfund site, near Milan, New Mexico [Aqueous U and Se concentrations were adjusted according to Harte et al. (2018a)]

U affecting well water concentrations, such as in wells Q (regional mills/mining), MV (local Homestake milling operation), and T11 (local Homestake milling operation). Further, mixing of Chinle Group waters may affect U and Se concentrations in water from several wells (ND, DD, DD2, and T11). The two wells that sample primarily alluvial aquifer waters, wells Q and MV, are affected by anthropogenic sources and transport of U. Therefore, there are no wells from our sample group that can be used to help identify natural sources of U in the alluvial aquifer waters alone because most are affected by mixing of some Chinle Group waters.

K and Th appear to be a better predictor of aqueous U concentrations than NGR or U from the SGR log (trolling measurements) based on regression. The mean aqueous U concentration from the passive samplers per well was plotted against the mean K, Th, and U from the SGR log per well (Fig. 8). An inverse relation is apparent between increasing K and Th from the SGR logs and the decreasing mean aqueous U concentration. We attribute the inverse relation to the presence of clays and its effect on the sorption of aqueous U and redox (tendency for more reduced conditions). The stacked measurements for Th also show an inverse trend (not shown; Harte et al. 2018b).

Discussion

The screen lengths of the 6 monitoring wells tested for this study are relatively long (> 20 ft or > 6.1 m) and intersect a heterogeneous aquifer of interbedded sands, silts, and clays (in some wells). The heterogeneity of the alluvium is identifiable by the variability in results of borehole geophysics measurements of NGR, SGR, and EM induction logs. The degree of mixing of groundwater is identifiable with the EM induction and fluid (conductivity and temperature) logs. The EM induction log was used to assess the degree of mixing in the formation, whereas the fluid logs were used to assess the degree of mixing in the well.

If the fluid log (either conductivity or temperature) showed a variation with depth so too did the vertical profile for chemistry for either U or Se concentrations from passive samplers; the exception was well DD2 that showed little fluid log variability but some variability in the vertical profile of U concentrations. We attribute the variability in aqueous U concentrations to depth-dependent redox processes. Iron-staining on the NS passive samplers from the exposure of oxygenated water in passive samplers to reduced waters in the well occurred in more than one-half of the samplers; this indicates

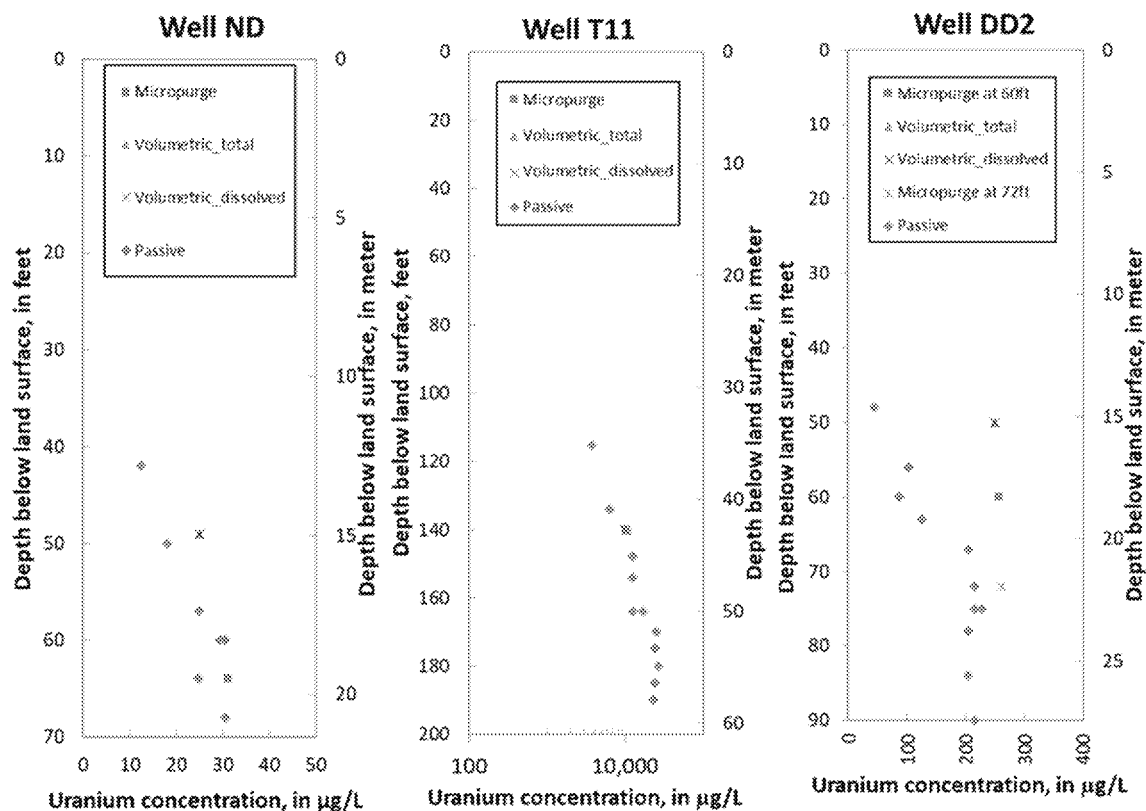


Fig. 7 Vertical profiles of aqueous U concentrations from passive samplers and concentrations from purge (micropurge and volumetric) samples, Homestake Superfund site, near Milan, New Mexico [Aqueous U and Se concentrations were adjusted according to Harte et al. (2018a)]

Table 6 Variation of natural gamma-ray (NGR) and spectral gamma-ray (SGR) to variation of aqueous U concentration from passive samplers, Homestake Superfund site, near Milan, New Mexico

Log	Units	Well name					
		Q	ND	DD	DD2	T11	MV
Mean gamma (NGR)	(API)	71.4	74.7	67.3	69.6	88.1	61.3
Stdevp gamma (NGR)	(API)	34.5	25.2	24.4	20.2	32.8	33.4
Mean K-spectral (SGR)	(pCi/gm)	17.1	23.5	16.5	14.6	11.6	15
Mean U-spectral (SGR)	(pCi/gm)	3.6	3.6	3.6	3.3	3.9	2.8
Mean Th-spectral (SGR)	(pCi/gm)	2.0	2.4	1.7	1.6	1.4	1.3
Mean concentration of U from the profile of passive samples excluding casing sample	(µg/L)	54.0	24	65	180	16,508	322
Standard deviation of U concentration from the profile of passive samplers excluding casing sample	(µg/L)	3.7	6.4	23.8	50.5	7,502.0	23.4
Mean concentration of Se from the profile of passive samples excluding casing sample	(µg/L)	411	65	163	13	121	28
Standard deviation of Se concentration from the profile of passive samplers excluding casing sample	(µg/L)	20.8	23.7	23.7	3.3	75.1	8.2

API American Petroleum Institute units, pCi/gm picocuries per gram, µg/L micrograms per liter, U and Se concentrations adjusted by Harte et al. (2018a)

that stratified inflow occurs. The most reduced waters would have the largest amount of ferrous iron precipitate onto the NS mesh of the sampler given that oxic water was used within the samplers promoting iron staining on the mesh.

Most of the wells capture mixed water from the alluvial aquifer and underlying Chinle Group; results show that only wells Q and MV primarily capture water from the alluvial aquifer. All the wells except for well Q are screened within

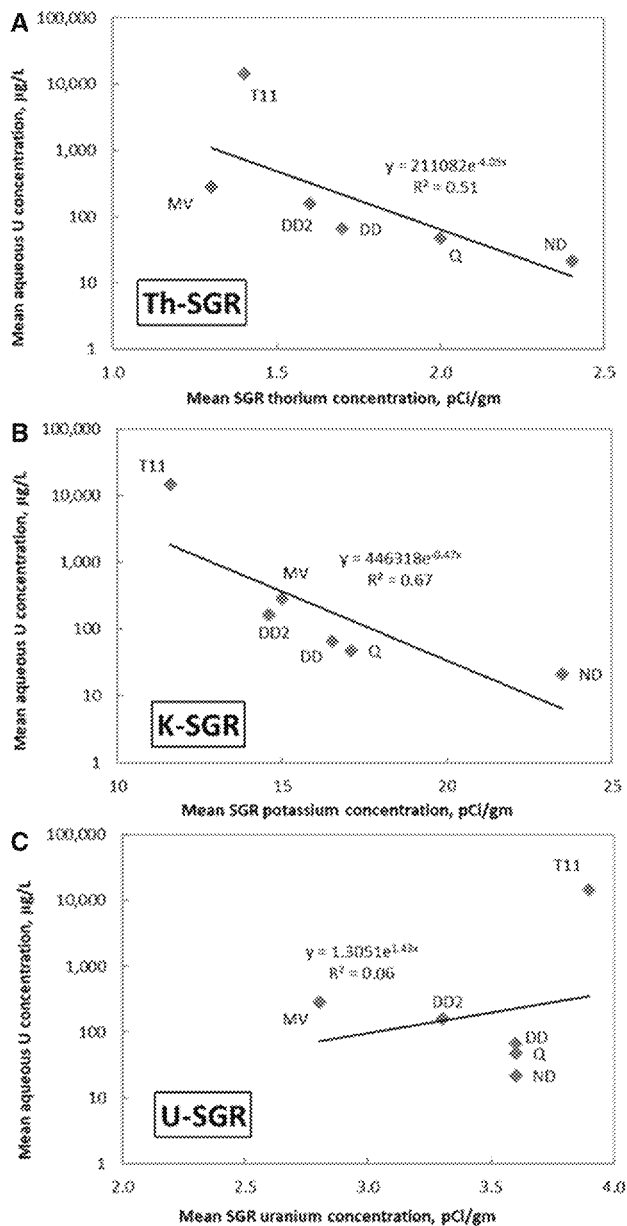


Fig. 8 Comparison of mean aqueous uranium (U) concentrations in micrograms per liter ($\mu\text{g/L}$) from passive samplers and mean spectral gamma-ray (SGR) measurements for thorium, potassium, and uranium in picocuries per gram (pCi/gm) for the screen opening of well, Homestake Superfund site, near Milan, New Mexico (Aqueous U and Se concentrations were adjusted according to Harte et al. 2018a)

or immediately overlying the underlying Chinle Group. The lithologic log for well MV is not available from the drilling record but based on the response of the NGR log, it is likely that this well is also drilled into the Chinle Group. Wells ND, DD, DD2, and T11 capture Chinle Group waters in addition to alluvial aquifer waters. Therefore, water samples reflect a mixture of alluvial aquifer and underlying Chinle Group waters. In some cases, the amount of water being

derived from the Chinle Group may be small relative to the alluvial aquifer water (e.g. well MV) yet contact with the Chinle Group may affect the geochemistry of the well water.

For aqueous U concentrations, the effect of capturing groundwater from the Chinle Group is dependent on the location of the well and whether the alluvial aquifer water U concentrations are relatively low ($< 100 \mu\text{g/L}$) or high ($> 300 \mu\text{g/L}$) at that location. Wells in the Chinle Group had concentrations of approximately $100\text{--}300 \mu\text{g/L}$ (Harte et al. 2018b). For aqueous Se concentrations, the addition of groundwater from the Chinle Group would tend to decrease concentrations. The influence of mixing of waters in the alluvium with upwelling of Chinle Group waters is visible at well ND. This well had an inverse profile trend in aqueous U concentration (increasing with depth) and aqueous Se concentration (decreasing with depth), which is indicative of an up flow of Chinle Group waters at this location. Analysis of time-varying capture during volumetric sampling (supplemental information s5) also supports this interpretation. In well DD2, aqueous Se concentrations are very low and can be attributed to upflow of Chinle Group waters or fault waters given its proximity to a fault (Fig. 1b). Alternatively, the low aqueous Se concentrations could also be attributed to early precipitation or sorption of Se on U roll-front type deposits (Brookins 1977). Selenium adsorption can be associated with iron hydroxides, which were visually observed on the NS mesh of the passive samplers.

A high U (pCi/gm) from the SGR logging was sometimes associated with high NGR (API). A high U ($> 5 \text{ pCi/gm}$) was found in red clays, other clay layers, brown sand, and in the basal alluvium and the underlying Chinle Group (Harte et al. 2018b). The mean U varied per well from a low of 2.8 pCi/gm in well MV to a high of 3.6 pCi/gm at wells Q, ND, and DD (Table 6). The narrow range of mean U concentration per well from the SGR indicates that U is ubiquitous in the alluvium and Chinle Group. However, K was the dominant radioactive element present. K varied from a low of 11.6 pCi/gm in well T11 to a high of 23.5 pCi/gm in well ND. Thorium and its relation to K is an indicator of clay mineralogy (Klaja and Dudek 2016). Thorium varied from a low of 1.3 pCi/gm (mean) in well MV to a high of 2.4 pCi/gm (mean) in well ND.

The mean Th as measured by the SGR logs was found to generally inversely relate to the mean aqueous U concentrations from the vertical profile of the passive samplers. This is an indicator of the presence of clays, reduced conditions, and U sorption. The higher the Th, the more likely that clays are present, and the greater the tendency for reduced conditions to be present.

Almost all the wells were found to contain some proximal source of U based on the SGR logs. The proximal source of U can be from the natural U occurrence or enrichment of U that was likely transported in groundwater from an

anthropogenic source and later sorbed. Wells likely affected by anthropogenic transport source of U from a distal location include wells Q and MV; well T11 is affected by a local anthropogenic source (LTP) of U.

Uranium isotope ratios of $^{234}\text{U}/^{238}\text{U}$ were low, suggesting a higher anthropogenic signature, at wells T11 (1.01), MV (1.07), and Q (1.18) as found by Harte et al. (2018b). Wells MV and Q had a relatively high relation of co-occurrence of aqueous U and Se concentrations from passive samplers indicating an anthropogenic signature. Uranium isotope ratios were higher, indicating a lower anthropogenic signature, in wells DD (1.53), DD2 (1.48), and ND (1.43). Wells with a ratio greater than 1.3 may be potentially unaffected by an anthropogenic U source or conversely subjected to upwelling and mixing of Chinle Group waters. Mixing of Chinle waters is likely based on this work at alluvial aquifer wells (DD, DD2, and ND). Therefore, relatively high $^{234}\text{U}/^{238}\text{U}$ ratios can be produced from the mixing of relatively low $^{234}\text{U}/^{238}\text{U}$ ratio alluvial waters and the mixing and the upwelling of Chinle Group waters with relatively high ratios. Waters from the Chinle Group had ratios > 2 in samples from several wells at the Site (Harte et al. 2018b). Therefore, a well that intersects a formation affected by milling could have a U isotope ratio indicative of U milling, which is typically a $^{234}\text{U}/^{238}\text{U}$ ratio near 1 but also intersect another formation unaffected by milling with a ratio of 2, which is indicative of unaltered U (Zielinski et al. 1997). If evenly mixed the resultant well water would have a ratio of 1.5.

Conclusion

Uranium (u) is fairly ubiquitous in the alluvial aquifer and underlying Chinle Group in the lower San Mateo Creek Basin near the Homestake Mining Co. Superfund site (Site). Uranium, as measured by SGR logging had similar values of pCi/gm in all 6 monitoring wells set in the alluvial aquifer and the Chinle Group. The exception was well T11 drilled through the LTP. The highest U concentrations (> 100 pCi/gm) from the SGR log were observed above the groundwater table in the tailings as detected in well T11. In two other monitoring wells, relatively high U (> 5 pCi/gm) were also found above the water table (wells DD and DD2).

Aqueous U concentrations appear to be inversely related to Th as measured by the SGR log. This indicates the possibility that U is bound in the clays, likely through sorptive processes. This may be partly redox related given the presence of clays and less oxic conditions, while unconfirmed, likely coexist. The reduced state of U, U(IV) is less mobile in groundwater than U(VI).

In wells DD and DD2, interbedded sands and clays may provide a role in exposing oxic waters to reduced waters

from the clay beds where U is likely immobile. The result would be the mobilization of U from the reduced form of U(IV) to U(VI). Core samples of formation would provide additional insight into this hypothesis.

Co-occurrence of U and Se aqueous concentrations provided insight into anthropogenic sources of U from mine and milling waste. Two of the wells, Q from regional mine/milling waters and MV likely from local milling waters, had the strongest relation between U and Se co-occurrence. One well, ND, showed an inverse relation indicating Chinle Group waters with relatively high U and low Se concentrations are upwelling into the well. Wells DD and DD2 showed a poor relation between U and Se and therefore show a relatively poor fingerprint of an anthropogenic source of U. However, in well DD2, the low Se concentrations could also be indicative of preferential Se sorption with iron-hydroxides as part of a roll-front type depositional process, which would obscure the relation with U. The interbedded sequence of clays and sand at that location could promote such a process.

More accurate determination of ambient U concentrations in the alluvial aquifer would benefit from monitoring wells with (1) shorter screens and less mixing of groundwater, and (2) targeted sampling of discrete units in the alluvial aquifer. For example, wells specifically screened in clay or sand layers, removed from direct contact with Chinle Group waters would allow for an improved determination of U concentrations for the alluvial aquifer from natural U sources. From the existing wells in this study, it was demonstrated that volumetric sampling methods were not needed to collect a representative sample from the formation and that volume-limited sampling methods, such as micropurge, is sufficient. Further, volume-limited sampling methods (conjunctive use of micropurge and passive sampling) can provide additional insight into the variability of U concentrations at the well scale.

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Message

From: Purcell, Mark [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=FE198E260B024EB4BD9D30DC11F900B1-PURCELL, MARK]
Sent: 10/8/2019 12:34:09 PM
To: Blake, Johanna MT [jmtblake@usgs.gov]; Harte, Philip [ptharte@usgs.gov]
Subject: FW: Final Published Paper on Homestake Site Background Ground Water - Johanna Blake - USGS
Attachments: Blake 2019 EES Differentiating Anthropogenic and natural sources of U by geochemical fingerprinting of GW at the Homestake U mill (002).pdf; Homestake supplemental (002).docx

Johanna, Phil,

As a follow up to my previous email, I note the information I sent to USGS. Some of Ron Linton's concerns are discussed below.

Mark

Mark D. Purcell

Superfund and Emergency Management Division (6SF)
U.S. Environmental Protection Agency - Region 6
1201 Elm Street, Suite 500
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From: Linton, Ron <Ron.Linton@nrc.gov>
Sent: Tuesday, October 08, 2019 7:29 AM
To: Purcell, Mark <purcell.mark@epa.gov>
Cc: Alexander, George <George.Alexander@nrc.gov>
Subject: FW: Final Published Paper on Homestake Site Background Ground Water - Johanna Blake - USGS

This is what you sent me. The supplemental info was in Word format, that is what gave me pause and reason to ask the question if it could go into ADAMS. The actual publication is marked as non-copyrighted, but the supplemental is not marked. I also didn't see any mention of the supplemental in the publication.

From: Purcell, Mark <purcell.mark@epa.gov>
Sent: Monday, September 23, 2019 12:22 PM
To: Tsosie, Bernadette <Bernadette.Tsosie@lm.doe.gov>; Linton, Ron <Ron.Linton@nrc.gov>; Alexander, George <George.Alexander@nrc.gov>; Kuhlman, Alison (CONTR) <Alison.Kuhlman@lm.doe.gov>
Cc: Kurt Vollbrecht (kurt.vollbrecht@state.nm.us) <kurt.vollbrecht@state.nm.us>; Longmire, Patrick, NMENV <Patrick.Longmire@state.nm.us>; Winton, Ashlynn, NMENV <Ashlynn.Winton@state.nm.us>
Subject: [External_Sender] Final Published Paper on Homestake Site Background Ground Water - Johanna Blake - USGS

All,

As discussed at our meeting in Grants last Wednesday, I have attached the final published USGS paper by Johanna Blake. Also attached is supplemental information that did not make it into the publication.

Please let me know if you have any questions or need additional information.

Mark

Mark D. Purcell

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Message

From: Purcell, Mark [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=FE198E260B024EB4BD9D30DC11F900B1-PURCELL, MARK]
Sent: 9/23/2019 4:21:57 PM
To: Tsosie, Bernadette [Bernadette.Tsosie@lm.doe.gov]; Linton, Ron [Ron.Linton@nrc.gov]; Alexander, George [George.Alexander@nrc.gov]; Kuhlman, Alison (CONTR) [Alison.Kuhlman@lm.doe.gov]
CC: Kurt Vollbrecht (kurt.vollbrecht@state.nm.us) [kurt.vollbrecht@state.nm.us]; Longmire, Patrick, NMENV [Patrick.Longmire@state.nm.us]; Winton, Ashlynn, NMENV [Ashlynn.Winton@state.nm.us]
Subject: Final Published Paper on Homestake Site Background Ground Water - Johanna Blake - USGS
Attachments: Blake 2019 EES Differentiating Anthropogenic and natural sources of U by geochemical fingerprinting of GW at the Homestake U mill (002).pdf; Homestake supplemental (002).docx

All,

As discussed at our meeting in Grants last Wednesday, I have attached the final published USGS paper by Johanna Blake. Also attached is supplemental information that did not make it into the publication.

Please let me know if you have any questions or need additional information.

Mark

Mark D. Purcell
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Message

From: Purcell, Mark [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=FE198E260B024EB4BD9D30DC11F900B1-PURCELL, MARK]
Sent: 7/19/2019 2:34:28 AM
To: hobbyhorse@grandecom.net
Subject: USGS Paper
Attachments: Blake 2019 EES Differentiating Anthropogenic and natural sources of U by geochemical fingerprinting of GW at the Homestake U mill (002).pdf

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Message

From: Purcell, Mark [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=FE198E260B024EB4BD9D30DC11F900B1-PURCELL, MARK]
Sent: 7/15/2019 3:39:58 PM
To: Earle Dixon [edixon@mcginnisandassociates.com]
Subject: USGS Paper - Homestake NPL Site Background Study
Attachments: Blake 2019 EES Differentiating Anthropogenic and natural sources of U by geochemical fingerprinting of GW at the Homestake U mill (002).pdf

Earle,

See attached file.

Mark D. Purcell
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Message

From: Purcell, Mark [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=FE198E260B024EB4BD9D30DC11F900B1-PURCELL, MARK]
Sent: 7/12/2019 8:53:37 PM
To: Travis, Pamela [Travis.Pamela@epa.gov]; Mekeel, Edward [mekeel.edward@epa.gov]
Subject: Second USGS Paper on Background Study - Homestake NPL Site
Attachments: Blake 2019 EES Differentiating Anthropogenic and natural sources of U by geochemical fingerprinting of GW at the Homestake U mill (002).pdf

Pam, Ed,

I have attached a copy of the second USGS paper by Johanna Blake on the Background Study for Homestake NPL Site. I sent it to key stakeholders today (Candace Head-Dylla – BVDA; Susan Gordon and Laura Watchempino – MASE; Tom Myers and Ann Maest – consultants to BVDA; Adam Arguello, Daniel Lattin, and David Pierce – Homestake; Theresa Ballaine and Joel Bauman - Rio Algom, Roy Blickwedel - GE).

NMED has received the paper from the USGS.

Mark

Mark D. Purcell
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Message

From: Purcell, Mark [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=FE198E260B024EB4BD9D30DC11F900B1-PURCELL, MARK]
Sent: 7/12/2019 8:47:22 PM
To: Ballaine, Theresa [Theresa.Ballaine@bhpbilliton.com]; Bauman, Joel [joel.bauman@bhp.com]; Blickwedel, Roy (GE Corporate) [Roy.Blickwedel@ge.com]
Subject: Second USGS Paper on Background Study - Homestake NPL Site
Attachments: Blake 2019 EES Differentiating Anthropogenic and natural sources of U by geochemical fingerprinting of GW at the Homestake U mill (002).pdf

All,

The second paper by Johanna Blake is completed for the USGS Background Study at the Homestake NPL Site. I have attached a copy.

Mark

Mark D. Purcell
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From: Purcell, Mark [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=FE198E260B024EB4BD9D30DC11F900B1-PURCELL, MARK]
Sent: 7/12/2019 8:43:24 PM
To: cheaddylla@gmail.com; Susan Gordon - MASE [sgordon@swuraniumimpacts.org]; Laura Watchempino [5000wave@gmail.com]; Tom Myers [tommyers1872@gmail.com]; Ann Maest [aamaest@gmail.com]
Subject: Second USGS Paper on Background Study - Homestake NPL Site
Attachments: Blake 2019 EES Differentiating Anthropogenic and natural sources of U by geochemical fingerprinting of GW at the Homestake U mill (002).pdf

All,

The second paper by Johanna Blake of the USGS on the background study at the Homestake NPL site is final. I have attached a copy.

Mark

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From: Purcell, Mark [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=FE198E260B024EB4BD9D30DC11F900B1-PURCELL, MARK]
Sent: 7/12/2019 8:38:27 PM
To: Arguello, Adam [aarguello@barrick.com]; Lattin, Daniel [dlattin@barrick.com]
CC: Pierce, David [dpierce@barrick.com]
Subject: Second USGS Paper on Background Study - Homestake NPL Site
Attachments: Blake 2019 EES Differentiating Anthropogenic and natural sources of U by geochemical fingerprinting of GW at the Homestake U mill (002).pdf

Adam, Daniel,

The second paper on the USGS Background Study by Johanna Blake is completed and to be published. I have attached a copy.

Mark

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